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Problems of presenting a college-level physics course in high school are considered. For possible solutions it draws upon the experiences of the schools which have included such courses in their curriculums. The following suggestions are made: 1) More laboratory experience should be provided than is usual in regular courses. 2) Heavy concentration and thorough understanding of mathematical principles are vital. 3) Intelligent administration is essential. 4) Scheduling must allow adequate time for lab and lectures, and classes should have a maximum of 15 students. 5) Teacher load must be smaller than is usual. 6) The teacher should be academically superior and devoted, with extensive and recent training. 7) Selection of students should be based on interest, aptitude, past performance, and completion of higher math courses.

A course outline and suggested lab experiences are included.

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ADVANCED PLACEMENT PROGRAM IN PHYSICS

New York State Education Department
Bureau of Secondary Curriculum Development
Albany, New York

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THE ADVANCED PLACEMENT PROGRAM IN NEW YORK STATE

This bulletin is one in a series designed to assist administrators and teachers in offering to academically superior students instruction of a caliber that is of post-secondary grade. It is trusted that such a program may indeed warrant advanced placement or credit upon entrance to college. This statement uses the College Entrance Board course description. In the introductory material those aspects most closely related with administrator and teacher experience have been stressed.

The New York State Education Department is indebted to the College Entrance Examination Board particularly those staff members who have charge of the advanced placement examinations and who have served as consultants on Department committees to prepare statements for advanced placement courses.

This bulletin was prepared by the Bureau of Secondary Curriculum Development in close cooperation with the staff of the office of science education and with helpful counsel from authorities in the Division of Higher Education of the Department.

Walter Crewson

WALTER CREWSON

Associate Commissioner

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FOREWORD

This statement is one of a series aimed at providing some guide lines to high school administrators and teachers who are planning to institute or have already instituted college-level courses in grade 12. While it is particularly directed at those schools offering such courses as part of the Advanced Placement Program of the College Entrance Examination Board, it is not limited to that program. It is not suggested that the addition of a college-level course in physics at the high school level is the best or the only curriculum adaptation that might be made in any given school system to provide for students with special abilities in science.

There are many problems related to the introduction of a college-level laboratory science course in the high schools. Few schools in the State have had experience with such a program. The following statement presents some of the problems, and for possible solutions, draws upon the experiences of the schools which have included such courses in their curriculum.

Preliminary plans for this Advanced Placement statement in physics were made by a group of consultants meeting with the staff of the Bureau of Secondary Curriculum. Hugh B. Templeton, Supervisor of Science Education, his staff and representatives of the office of Elbert K. Fretwell, Jr., Assistant Commissioner for Higher Education, were also present. The consultants were:

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The laboratory experiments that are provided in this publication were written by Thomas D. Miner, Garden City High School and reviewed by W. Robert Kelley, supervisor of programs for the gifted. Drawings were prepared by Herbert A. Steinke, formerly supervisor of art, Albany Public Schools. The manuscript was written by Robert MacGregor, associate in science education and Herbert Bothamley, associate in secondary curriculum who also organized and edited the final draft.

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ADVANCED PLACEMENT PROGRAM IN PHYSICS

The advanced placement course in physics offers excellent stimulation and challenge for the truly superior students; it is needed to broaden their academic horizons. It is only through rigorously planned and executed college-level advanced placement courses that superior students will earn the rewards of their efforts by receiving college credit and/or placement. It is possible for some students upon entering college to omit their freshman course and start with an advanced course. In some instances, they can receive credit towards college graduation.

The advanced placement course should offer a more mature and sophisticated presentation of content and provide for much more extensive laboratory experiences than is normally found in a secondary school course of study. The advanced placement course in physics is intended to be a rigorous, well-disciplined undertaking that will challenge fully the capabilities of the most competent students. A heavy concentration and thorough understanding of mathematical principles is vital to successful achievement in college physics.

GENERAL ADMINISTRATIVE CONSIDERATIONS

Sympathetic and intelligent administration of any advanced placement program is essential to its success. Special considerations must be given by the administrator in order to establish an effective advanced placement program. Adequate time must be allotted for both class and laboratory sessions. Scheduling will, of necessity, vary from school to school, but it is strongly recommended that at least two double laboratory periods (100 minutes where possible) be provided in addition to three or four recitation periods (200 minutes where possible). Generally, class enrollment should be maintained at a maximum of 15 students. This permits individual pupil participation and creative "open-ended" laboratory experiences.

The availability of adequate laboratory assistance in the form of released time or personnel is of great importance. It is essential that certain supplies, equipment and material beyond those that are normally used in the physics laboratory be provided.

Inasmuch as the teacher of an advanced placement course must devote time far in excess of that required for ordinary class preparation, every effort should be made to lessen the number of programmed hours. Program allowance may take several forms, the best one being arrived at in individual school situations. It is well to keep in mind that as a general rule the teaching preparation involved in one period of an advanced

placement course including laboratory, is equivalent to that of two regular class periods. Financial assistance and released time should be given to the advanced placement teacher in order that it will be possible for him to participate in conferences and workshops relating to the teaching of such courses.

The use of textbooks and other supplementary materials is essential. The use of periodicals such as American Journal of Physics, Physics Today and Scientific American will aid the teacher with valuable current developments in the field. The bibliography on page 105 contains a listing of helpful texts and supplementary books for students and teachers. However, this represents only a limited number of the many excellent publications that are available.

SELECTION OF TEACHERS

The success of any advanced placement program will depend largely upon the energies and efforts of an academically superior, highly qualified and devoted teacher for whom the program will become a truly rewarding educational experience. To be selected for teaching an advanced placement course in physics a teacher:

- Should present a broad background in the physical sciences supplemented by recent training in advanced courses in physics and mathematics
- Should be cognizant of the problems and major trends in the teaching of "modern" physics and have a keen awareness of its relationships to other disciplines
- Should have demonstrated unquestionably that he possesses superior teaching ability as determined by previous teaching performance
- Should have that undefinable quality which challenges students to explore and see new relationships where none were observed before
- Should be enthusiastic and endowed with physical vigor
- Should be in philosophic harmony with the aims of the program

SELECTION OF STUDENTS

The heavy responsibilities placed upon the student by the exceedingly demanding quality and quantity of a college-level course mandates the desirability for setting high standards

for admission to a course in the advanced placement program. It should be remembered, however, that no one set of criteria will serve in its entirety for the selection of all candidates in all school situations. To be selected for an advanced placement course in physics a student:

- Should have demonstrated a strong interest in, and motivation for science, especially physics, and an eagerness to work consistently on his highest level of ability. (Intensely motivated students will be willing to devote considerable extra time and effort to reading and research. This is probably the single most valid criterion for student selection.)
- Should have a significantly high level reading ability. (This may defined as a level well above the average as determined by reading scores on standardized reading tests over an extended period in the student's schooling.)
- Should have successfully completed the first course in physics (with a Regents grade of at least 90) and chemistry as prerequisites. (In addition, should have completed Mathematics 11 with a Regents grade of at least 90 and be currently enrolled in (or have completed) Mathematics 12.
- Should have a minimum I.Q. of 125. (By no means should this criterion become the sole deciding factor expecially on the basis of a single score, and particularly if students have satisfied the above criteria.)
- Should have a record that contains quality recommendations from former teachers with stress placed upon objective evaluation insofar as possible.
- Should not be so involved in time-consuming extra-curricular activities that the usual burden of a college-level course makes demands on his time that he cannot fulfill.

THE LABORATORY PROGRAM

A cardinal principle in planning the laboratory work of the course is to create those conditions which will enable

students to work independently. The laboratory experiences must provide the students with extensive opportunities to study a wide assortment of physical situations. Through such experiences they will be able to strengthen the concepts and understandings developed in class recitations and supplementary readings. Adequate time, supplies and equipment must be provided in order to make possible individual work. The nature and extent of laboratory work will, of necessity, depend upon the order in which topics are investigated in class recitations.

A formal laboratory program based upon experiments normally performed at the college level is essential. The laboratory exercises found at the end of the section on Content (page 16), should provide the teacher with some suggestions necessary for carrying out experiments that are designed for this level.

THE ADVANCED PLACEMENT PROGRAM OF THE COLLEGE ENTRANCE EXAMINATION BOARD

Each year in May an examination is given by the College Entrance Examination Board covering the material in advanced placement programs. This examination is three hours in length; one hour of which is devoted to objective questions and two hours to essay questions. Any student may take this examination. Those students who have not had a formal course in advanced placement are not excluded from it but unless they have exceptional background and ability they should not be encouraged to try it. A committee composed of college and high school teachers grades the examinations utilizing a five-point scale in the evaluation:

5 - indicates highest honors

4 - honors

3 - creditable

2 - passing

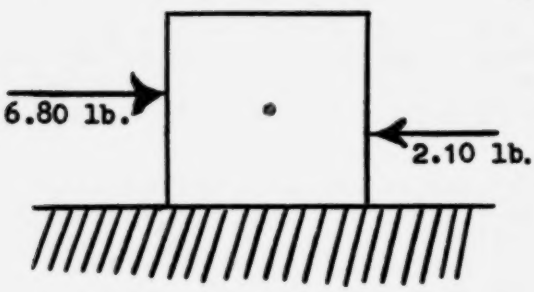
1 - failing

Colleges base their decisions to grant advanced placement and/or credit upon several factors. During the summer the college indicated by student choice receives the following: examination grade, a copy of the examination administered the previous spring, the student's essay booklet, a description of the course prepared by the teacher in the advanced placement subject, the grade received in the course and the recommendation of the high school principal. Occasionally, colleges also design and administer their own supplementary advanced placement tests.

EVALUATION

In general, it is undesirable to coach students for the advanced placement examination. Students should, however, become familiar with typical questions of the examination. The teacher should exert effort to include on his own tests those questions which will demand the students' utmost ability in framing competent answers. Students should be urged to be proficient in writing well-organized and mathematically correct derivations and solutions to problems. Care should be taken in developing logical sequence in order to avoid meaningless rambling discourses. Two typical advanced placement essay questions are given below:*

1. A body which weighs 54.3 pounds rests on a horizontal frictionless plane. Forces of 6.80 and 2.10 pounds act as shown.



(a) Define the term "weight of the body." Then use this definition together with any necessary additional ideas to calculate the mass of the body. Explain what you are doing, and in the course of the explanation, define the unit of mass in the system which you use.

(b) Sketch the body alone, showing all the forces acting on it. Mark the given forces with their known numerical values and label unknown forces with symbols.

(c) Calculate the magnitude of any unknown forces shown in (b), stating what principles are applicable and showing clearly how you apply them in this case.

(d) Examine (b) qualitatively to determine whether or not any acceleration will be imparted to the body. Indicate your conclusion and justify it. If you conclude that acceleration will be imparted, calculate its value, showing clearly what principles are applied and how the application is carried out. (Remember that acceleration is a vector quantity and be sure that your final statement of its value is complete.)

2. In a cyclotron, ions pursue circular paths in a uniform magnetic field (perpendicular to the plane of the path).

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* College Entrance Examination Board. Advanced placement program: course descriptions. The Board. 1960

(a) State an expression (1) for the force exerted by the field on such an ion and (2) for the centripetal acceleration.

(b) Show by an algebraic discussion that the time an ion takes to travel once around is independent of its speed or energy. List your assumptions or starting-points clearly.

(c) Describe briefly the use made of this property in cyclotrons.

(d) Mention any limitations of this property that you know.

It is strongly recommended that all students enrolled in the advanced placement physics course take the advanced placement examination at the time it is administered.

Both student and teacher evaluation should be the goal of all tests whether written or oral. One effective means whereby a test becomes a learning experience is to arrange conference time to be used for discussion of the student's self-evaluation and progress.

Because of the unusually rigorous nature of the advanced placement course the grade earned should be excluded when determining high school honors and/or rank within the class. Some indication should be made on the student's record as to the status of the course and whether or not the grade indicated is the college equivalent of the high school mark.

THE POST EXAMINATION PERIOD

During the last weeks of school after the advanced placement examination has been given, teachers and students should be encouraged to use this time effectively. It is suggested that consideration be given to allowing students to extend their scope of interest. Detailed reports could well be prepared and individual students could take over certain class periods to present to the class the results of their investigations. In no case should the post-examination time be allowed to to to waste. On the contrary, it should provide for extremely effective sessions of the course; this has been a common experience of teachers working with advanced placement programs.

CONTENT

The coverage of many detailed topics is less important than the development of a mature understanding of the basic principles and methods in the advanced placement physics course. The stress

is placed upon the level of thought rather than any particular listing of subject matter. A quantitative approach should be used wherever possible and all derivations should be developed with the greatest care.

The College Entrance Examination Board acknowledges the difficulty in establishing too definite listing of subject matter to be presented in an advanced placement course in physics. The Board feels that an attempt at broad coverage will defeat the main objectives of college physics; namely, (1) to develop in the students an appreciation of physics as a process of inquiry, and (2) to provide them with a resource depth of understanding of certain important concepts and principles.

It is extremely difficult to prepare a specific content outline because (1) some pupils have had the PSSC physics course as their first course, while others have taken the conventional Regents course, (2) "modern physics" is introduced in some first year physics courses to a greater extent than in others, (3) the order and treatment of topics vary so widely, (4) colleges offer a wide variety of types of physics courses.

All available opinion indicates that the Advanced Placement course should contain the following features:

- The course should demand frequent use of mathematical tools including: the slide rule, algebraic, geometric and trigonometric relationships, and vector analysis.

  The place of the calculus in the Advanced Placement course remains in doubt. In event that the pupils are enrolled concurrently in a calculus course, it is suggested that frequent use be made of this tool in the physics course.

- Selected topics from each of the major areas of physics should be studied in depth. Within the time available no textbook can be covered in its entirety.

- There should be no needless duplication of material from the elementary physics course.

- At least one-third of the time should be allotted to the presentation of the areas of mechanics since most of the remaining topics are related directly or indirectly to mechanics.

A wide variety of course outlines can be developed based upon the broad outline designed at the Carleton Conference. This conference was held at Carleton College, Northfield, Minnesota on September 5-8, 1956. Thirty-seven participants deliberated "on the improvement of the quality and effectiveness of introductory physics courses." Membership on the committee included representatives from: American Association of Physics Teachers; Optical Society of America; Society for Engineering Education; and physicists from research laboratories and industrial concerns.

Three suggested interpretations of the outline appeared in the American Journal of Physics, volume 25, 1957. This report contained the following broad outline of a course of study which the New York State Advanced Placement Physics Committee endorsed as being a suitable framework for a course of study in Advanced Placement in Physics:

- Conservation of momentum
- Conservation of mass and energy
- Conservation of charge
- Waves
- Fields
- The molecular structure of matter
- The structure of the atom

In addition the group suggested "optional" topics which could be included if time permitted:

- The electromagnetic theory of radiation
- The second law of thermodynamics
- The special theory or relativity
- Quantum theory

It will be noted that the outline is sufficiently broad to encompass most specialized topics taught in college courses and listed in the index of any widely used textbook. The general nature of the outline is intended to encourage the choice and organization of specific topics from the point of view of teaching physics as a coherent intellectual discipline. Treatment in depth of a limited number of topics is preferable to an encyclopedic survey.

An adaptation of one interpretation presented in the report follows:

Possible Outline A

I. Kinematics

A. Speed and Acceleration
1. Measurement and "errors"
2. Motion with constant speed
3. Instantaneous speed
4. Equations of motion for constant acceleration

B. Kinematics of Free Fall and Projectile Motion
1. Simple trajectories
2. Vector algebra
3. General projectile motion

II. Dynamics

A. Newton's Laws of Motion

B. Rotational Motion
C. Newton's Law of Universal Gravitation

III. The Conservation Principles

A. Conservation of Mass
   1. Collisions
   2. Mass-energy relation
B. Conservation of Momentum
   1. Collisions
   2. Angular momentum
C. Conservation of Energy in Mechanics
D. Heat Phenomena
   1. Temperature
   2. Heat transfer
   3. Change of state
   4. Calorimetry
   5. First law of thermodynamics

IV. Waves

A. Wave Motion in General
   1. Reflection
   2. Refraction
   3. Interference
B. Electromagnetic Waves. Physical and Geometric Optics
C. Vibrating Strings and Columns. Sound

V. Fields in Electricity and Magnetism

A. Concepts of Field and Charge
   1. Force-distance Law
   2. Coulomb's experiments
   3. Conservation of charge
B. Electrostatics
   1. Field strength
   2. Potential
C. Electric Currents
   1. Magnetic fields
   2. Current-field interaction
   3. Electromagnetic induction
D. The Electron
   1. Cathode rays
   2. Measurement of e/m
   3. Measurement of e

VI. Molecular Structure of Matter

A. Laws of Gases
B. Avogadro's Hypothesis
C. Kinetic Theory of Matter and Heat

VII. Atomic Structure

- A. Rutherford's Atomic Model
  - 1. Scattering experiments
  - 2. Nuclear charge and size
- B. Quantum theory of Planck and Einstein
- C. Bohr's Theory
  - 1. Energy levels
  - 2. Atomic size
  - 3. Emission and absorption spectra
  - 4. Periodic table
- D. Spectral Series
- E. Equivalence of Mass and Energy

Note that the failure to include many topics treated in many college courses (statics, alternating current, thermodynamics and others) indicates one individual point of view and is not intended as a recommendation to eliminate these, or any other, topics from Advanced Placement Courses in general.

The following possible outline is one developed by a member of the New York State Advanced Placement in Physics Committee. This course of study has been used successfully in a New York State school for several years. The only alteration is a rearrangement of the topics to conform approximately to the arrangement of topics in the Carleton Report. The arrangement used in the outline does not necessarily suggest the order in which the topics are presented.

Possible Outline B

I. Conservation of Momentum, Mass and Energy
- A. Vectors
- B. Statics
- C. Rectilinear Motion and Trajectories
- D. Mechanical Energy
- E. Newton's Laws of Motion
- F. Impulse and Momentum
- G. Circular Motion, Rotation and Gyroscopes
- H. Elasticity and Collisions
- I. Simple Harmonic Motion
- J. Hydrostatics and Hydrodynamics
- K. Elementary Thermodynamics, Carnot's Cycle and Entropy

II. Conservation of Charge

- A. Charge, Field Intensity and Potential
- B. Kirchoff's Laws
- C. Electronics

III. Waves

A. Interference and Diffraction
B. Refraction and a General Treatment of Lenses
C. Electromagnetic Waves
D. Alternating Currents
E. Thermal Radiation

IV. Fields

A. Magnetic Fields and Induced E.M.F.
B. Other Fields

V. Molecular Structure of Matter
A. Kinetic and Molecular Structure
B. Thermal Behavior of Ideal Gases

VI. Structure of the Atom
A. Quantum Phenomena
B. Photoelectric Effect
C. Spectra

SPECIAL LOCAL CONSIDERATIONS

A PARTIAL LISTING OF POSSIBLE LABORATORY EXPERIMENTS

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As indicated previously, the laboratory program should be based primarily upon experiments performed at the college level as described in typical college laboratory manuals. Adequate equipment and facilities should be provided to accomplish this objective wherever possible.

The following descriptions of laboratory experiments illustrate suitable exercises that require a sufficient depth of treatment but frequently little or no elaborate equipment. Some of these experiments may be incorporated in the laboratory program as substitutes for experiments that require unavailable equipment or as supplementary exercises. It is not intended that a complete laboratory program be based upon the experiments that follow.

The American Journal of Physics provided original data for many experiments outlined herein. It is urged that teachers consult this, as well as other journals, for new and revised experiments which may be applicable to the course.

I. EMPIRICAL RELATIONSHIPS

The student of physics should be introduced to empirical methods early in the physics course. The actual subject of investigation for this purpose is not very important. Preferably it should be beyond the pupil's experience to that date, so that he does not have prior knowledge of the result to be expected. It should not present unusual difficulties of either manipulation or equipment, and the mathematical nature of the relationship to be derived should not be too baffling. If it covers a subject that will be treated analytically later in the course, so much the better.

While almost any laboratory situation can be approached empirically, three specific problems which have proven useful will be presented.

(1) Simple Harmonic Motion. Before the study of simple harmonic motion, the student may be asked to find the relationship between the period of a mass bobbing on a spring and the magnitude of the mass. Obviously, all that is needed is a coiled spring, a set of masses, a timer, and several sheets of graph paper. Data is taken and found to be nonlinear. It is then guessed that the relationship has the form:

$$T = am^b$$

where a and b are constants. If a and b can be determined, the problem is solved. The values of b may be arrived at by trial and error, but it is much neater to find them graphically.

Taking logarithms of both sides of the hypothesized equation:

$$\log T = \log a + b \log m$$

Now, if the relationship is as guessed, a graph of log T against log m approaches linearity, with b the slope, and log a the intercept on the log T axis. In this way both constants are determined, and a check of the final equation against the data should prove satisfactory. Instead of plotting logarithms on the usual coordinate paper, logarithmic paper may be used directly.

This experiment is capable of considerable expansion. The next question posed is "What factors determine the value of a?" Obviously, the nature of the spring must be involved here, and a second experiment with a single mass and a selection of springs is performed, to find how the period varies with the spring constant. For this analysis we propose a new equation:

$$T = c \sqrt{m}\, k^d$$

where c and d are new constants, m is the mass, and k the spring constant. Since the mass is constant, and we have already found b to have the value $\frac{1}{2}$, we write the new equation as above. The intercept of the new logarithmic graph is thus $\log \left(c \sqrt{m} \right)$, and the slope is d. It is a gratifying surprise to most pupils when c turns out to be 2π.

A further extension is possible if the pupil is reminded that the spring is also oscillating along with the attached mass, and so the mass of the spring must have something to do with the relationship. If T^2 is plotted against m, the mass

of the spring shows up as an intercept on the m axis. Ideally, the effective mass of the spring is 1/3 its actual mass, but pupil measurements are seldom precise enough to arrive at this fraction.

One may also arrive at the effect of the spring mass by making a very loose spring, and allowing it to oscillate with no added mass attached. The previously arrived at equation for the period can then be applied to find the effective mass. This may then be compared with the actual mass. Spring brass wire as it comes off the spool can be used for this kind of spring.

(2) Power in a Lamp. A second problem which may be presented is, "Find the relationship between the power developed in an operating incandescent lamp and the resistance of its filament."

The circuit is the usual ammeter-voltmeter circuit. Readings are taken for a series of operating voltages, ranging from perhaps a quarter of the normal lamp voltage up to and even slightly exceeding the rated voltage. If the voltmeter resistance is not high, ammeter readings should be corrected for the voltmeter current.

The graph of lamp power against resistance is not linear and invites considering an equation of the form:

$$P = a R^b$$

This time, trial and error efforts to determine b are likely to be frustrating, because b is, in general, not an integer. Use of a logarithmic graph will straighten it out and permit evaluation of the constants.

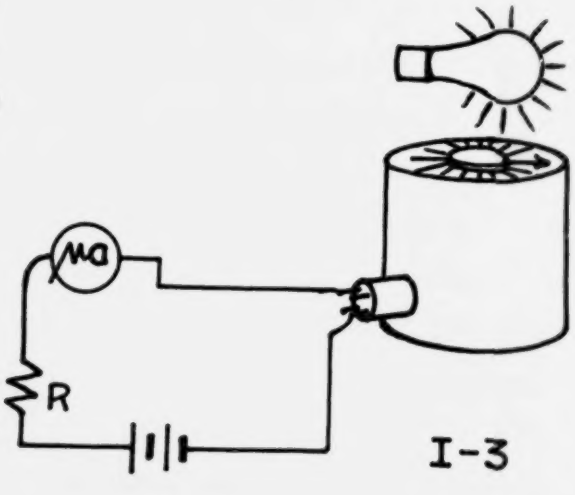
The values of a and b depend upon the lamp being used. For a certain three-volt flashlight lamp the proper relation turns out to be:

$$P = 0.0074\ R^{2.69}$$

It is interesting to have different members of the class use different types of lamps.

(3) Malus' Law. A third situation which is interesting to investigate empirically is that of Malus' Law; the relationship between the intensity of light transmitted by a polarizer and analyzer and the angle of rotation of either from the position for which intensity is maximum.

The apparatus consists of a source of light, two polaroid disks, a scale for measuring the angle between the transmission directions of the two disks and a means of measuring the intensity of the transmitted light. A simple physical arrangement is suggested in diagram I-3 The light source is a 60-watt incandescent lamp. The transmitted light falls on a photoelectric cell and its intensity is indicated by a microammeter or galvanometer in the circuit. R is a protective resistor which may be about 0.5 megohm. The cell is hooded from room light by insertion in a hole in the side of a short length of cardboard mailing tube.



I-3

The top of the tube is covered by another piece of cardboard with a hole in its center the size of the aperture of the polaroid disks. The analyzer is fastened to the bottom of the cover under this opening. It is not necessary to mark its orientation. The polarizer rests on top. The top of the cover has two protractors or a sheet of polar coordinate paper cemented to it. The polarizer is equipped with a pointer so that its angular position can be read on the scale.

Intensity measurements are made as the polarizer is rotated through 360 degrees. A graph of intensity against angle of rotation shows a curve with an apparently sinusoidal shape. Consideration of the elementary facts of polarization suggests that, since the intensity is a maximum when the two disks have their planes of polarization coincident, the desired function is most likely the cosine. The indicated relationship then is:

$$I = I_{max} \cos^n \theta$$

The angles are then corrected so that the position of maximum intensity corresponds to $\underline{\theta} = \underline{0^\circ}$, and a graph of log $\underline{I}$ against log $\underline{\cos\theta}$ is drawn. This shows that the value of the exponent is $\underline{2}$, and a subsequent graph of intensity against $\underline{\cos^2\theta}$ gives a straight line. Malus' Law, which is not given in all elementary texts is:

$$I = I_{max}\cos^2\theta$$

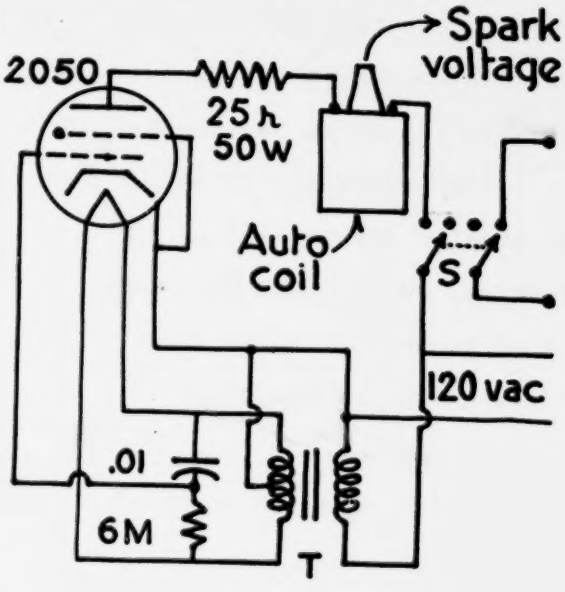
II. THE ACCELERATION DUE TO GRAVITY

The acceleration of gravity can be measured in many ways, most of which are well known and need no explanation. The purpose of this section is to present several techniques which can be adapted to the measurement, either to simplify the equipment , or to involve more than usually challenging situations.

(1) The Freely Falling Body. The free fall apparatus which allows a falling object to trace a timing record of some sort on a stationary strip is offered in catalogs. A modification of this, in which the recording paper falls through a stationary spark gap can be assembled quite easily. A strip of waxed recording paper has a weight attached to one end and is supported from the other end. The spark gap is just above the weight at the center of the paper. The paper is released and at the same instant the timing spark is started. Thus the paper trails behind the falling weight and the spark punches a train of holes in the paper giving a record similar to that produced by the more elaborate apparatus.

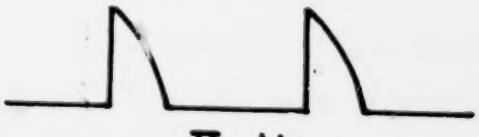
The only special equipment needed is a periodic spark producing device. The best arrangement is a contactor driven by a synchronous motor used in the primary circuit of a spark coil. These devices are available commercially. An inexpensive, but satisfactory electronic substitute can be constructed. It uses a thyrotron in the primary circuit of an automobile spark coil. The sparking frequency is the ac line frequency. In diagram II-1a, T is a 6.3 volt center tapped

filament transformer. This is used not only to supply power for the tube filament, but also for the grid voltage. The capacitor and resistor across its secondary are rather critical and should be selected to give an RC product of 6×10^{-3} within $\pm$ 2 percent. The switch in the plate circuit is a double pole, double throw switch with spring return from one side. In its normal position it holds the thyrotron circuit open and an auxiliary circuit closed. This auxiliary circuit is used to operate an electromagnet which will hold the top of the record paper for the falling body experiment.



II-1a

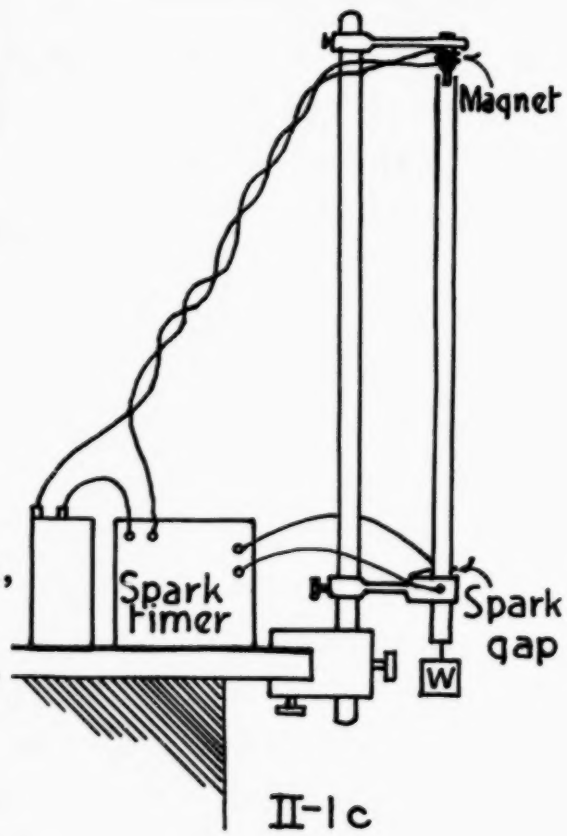
Before operating this timer, it is essential to make sure that the phasing of the grid voltage is correct. Temporarily replace the 25-ohm resistor with a 200-ohm resistor and connect an oscilloscope across it. If the pattern seen when the unit is operated is that of typical half wave rectification, the grid phasing is wrong. The scope should show a very small portion of each alternation, as in diagram II-1b. Incorrect phasing is corrected by reversing the primary leads of the transformer. If this is not done, the


II-1b

tube may be ruined. When the pattern is as shown, the 25-ohm resistor is replaced, and the timer is ready for use. Reducing the resistance in the plate circuit will increase the spark length, but in no case should it be less than 17 ohms.

The spark gap is two or three millimeters wide. A piece of plastic may be bent in a U-shape, and machine screws, filed to points on the ends in order to define the gap, screwed through the opposite ends of the plastic toward each other.

The paper, which is about a meter long, is supported by a small electro-magnet. An easily devised clip, made of magnetic material, holds the paper to the magnet. The magnet is operated from any convenient dc source, through the auxiliary switch shown in the spark timer diagram.



II-1c

Arrange the apparatus as shown in diagram II-1c. The spark gap is adjusted with the paper in place, so that it is directly under the magnet, and the paper hangs freely, not bearing against either side. The weight is as large as is reliably supported by the magnet. When the switch is thrown

the magnet releases the paper and simultaneously starts the timer. The spark record is then analyzed in the usual way to bring out the nature of uniform acceleration, and to make a measure of g.

Once the apparatus is set up and adjusted, records may be made quickly, so that each member of a class may have his own record tape for analysis.

(2) The Whirling Weight. A very instructive measure of g can be done by whirling a weight in a vertical circle at a speed just sufficient to cause the string to go slack at the top of the circle. At this instant the centripetal force is supplied by the weight, and

$$mg = \frac{mv_1^2}{r}, \text{ or } g = \frac{v_1^2}{r}$$

where v_1 is the velocity of the mass at the top of its path and r is the radius of the path. The average velocity in the circle is $\frac{1}{2}(v_1 + v_2)$ where v_2 is the velocity at the bottom of the path. This maximum velocity v_2 can be expressed in terms of the minimum velocity v_1 by writing an energy equation:

$$\tfrac{1}{2} mv_2^2 = \tfrac{1}{2} mv_1^2 + 2mgr$$

from which,

$$v_2^2 = v_1^2 + 4gr$$

since $g = \frac{v_1^2}{r}$, this becomes

$$v_2^2 = v_1^2 + 4r \frac{v_1^2}{r} = 5v_1^2$$

Then the average velocity in the circle is

$$\frac{2\pi r}{T} = \frac{v_1 + \sqrt{5v_1}}{2} \quad \text{or}$$

$$v_1 = \frac{4\pi r}{3.24T}$$

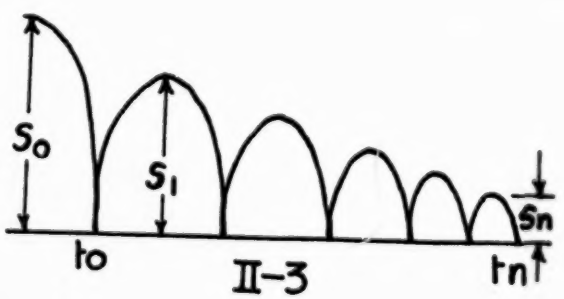
where T is the period of the orbiting object. Substituting this in the original equation for g we have:

$$g = \frac{v_1^2}{r} = \frac{1}{r}\left(\frac{4\pi r}{3.24T}\right)^2 = \frac{15.1r}{T^2}$$

An object is tied to a strong cord about a meter long. With a little practice this can be spun in a vertical circle at such a speed that the string is felt to be under no tension at the top of the circle. The weight should not actually leave its circular path at the top and any real jerk in the string is a sign that the velocity is not great enough. The period is obtained by timing a counted number of revolutions and the radius is measured from the point at which the string is held to the center of the weight.

(3) The Bouncing Ball. Another ingenious way of measuring g is by timing the bounces of a ball. The time required for a ball to make a certain number of successive bounces depends upon the height of its first bounce, the coefficient of restitution, the number of bounces and g. The first three quantities can be measured and used to yield a value for the last.

Diagram II-3 shows the path of a ball making repeated bounces after falling from height S_o. The coefficient of restitution, e, is given by:



II-3

$$e = \sqrt{\frac{S_1}{S_o}}$$

or, if it remains constant (nearly true for a uniform ball)

$$e = \sqrt{\frac{S_n}{S_n - 1}} \quad \text{or} \quad \sqrt{S_n} = e \sqrt{S_n - 1}$$

From the laws of motion, the time between successive bounces is seen to be:

$$t = 2\sqrt{\frac{2s}{g}}$$

Thus the total time from $\underline{t_o}$ to $\underline{t_n}$ is:

$$T = 2\sqrt{\frac{2}{g}} \left[\sqrt{S_1} + \sqrt{S_2} + \text{------} \sqrt{S_n} \right]$$

Since each term in the bracket is the product of the preceding term and the coefficient of restitution, we have

$$T_n = 2\sqrt{\frac{2S_1}{g}} \left[1 + e + e^2 \text{--------} e^n - 1 \right]$$

The summation of this geometric series when $\underline{n}$ is a finite number, gives:

$$T_n = 2\sqrt{\frac{2S_1}{g}} \left(\frac{1 - e^n}{1 - e} \right)$$

and solving for g we have:

$$g = \frac{8S_1}{T_n^2} \left(\frac{1 - e^n}{1 - e} \right)^2$$

The coefficient of restitution is first found by measuring the height to which the ball bounces after having been dropped from a known height, and applying the formula:

$$e = \sqrt{\frac{S_1}{S_o}}$$

This should be checked for various heights to make sure that $\underline{g}$ for this particular ball and surface does not show a large systematic variation as the height changes.

The ball is then dropped from a known height, the timer is started at the first contact with the floor, and as many bounces as can be followed are timed. S_1 may be measured, or computed from the known value of S_o and g.

III. CONSERVATION OF ENERGY

When an object accelerates in rolling or sliding down an incline, its increase of kinetic energy is at the expense of its original potential energy. The energy expended against friction also comes from the same source. Applying the law of conservation of energy, we may say that if an object starts from rest, its potential energy at the top of the incline, using the base of the incline as the reference level, equals the sum of its kinetic energy at the foot of the incline, and the work done against friction, or:

$$mgh = \tfrac{1}{2} mv^2 + sf$$

where m is the mass of the object, g the acceleration due to gravity, h the vertical height of the object's starting point above the base of the incline, v its final velocity, s the distance it moves along the slope and f the force of friction.

The incline should be as long as is practical. If the object is to move by sliding, the surface of the slope must be very uniform, and kept that way during the experiment. The sliding object may be a wood block, or other smooth-surfaced object. A metal cap from a peanut butter or mayonnaise jar has a uniform and flat surface, and loaded with a 200 gm. weight makes a good sliding object. A "Hall's Carriage" can be used as the object moving down the plane if its bearings are tightened so that the wheels turn smoothly but not freely. The bearings must not be so tight that the wheels slide, rather than roll, however. A sphere or cylinder should not be used for the moving mass because the angular momentum involved would

have to be considered in the conservation equality. A meter stick and stopwatch are also needed.

First measure the friction by increasing the angle of the plane until the object moves down without acceleration. The coefficient of friction (μ) for those surfaces and with motion at that speed is then equal to the tangent of the angle. Then raise the incline, measure its dimensions, and starting the object from rest, time its motion over a measured distance. Its final velocity can be computed from the distance and time, assuming uniform acceleration. The energy equality to be checked is:

$$mgh = \tfrac{1}{2}mv^2 + \mu(mg \cos \theta)s$$

It is instructive to add complexity to the situation. If a pulley is mounted at the top of the incline, a cord can be passed from the object over the pulley to a hanging weight. By selecting the size of the weight, the object can be caused to accelerate either down or up the incline. It must be remembered that not only is the potential energy of the hanging weight being changed, but also its velocity and consequently its kinetic energy.

For the student who wishes to become really involved, suggest that he measure the final velocity of the object sliding on the incline by allowing it to plunge from the end of the plane at table-top height to the floor, and calculating the velocity from the height of the table and the distance moved by the object horizontally before hitting the floor. The angle at which it enters its period of free fall is the angle of inclination of the plane. The pulley and hanging weight are not used in this version of the experiment, and the sliding object must be one that will not be damaged, and will not damage the floor when it strikes.

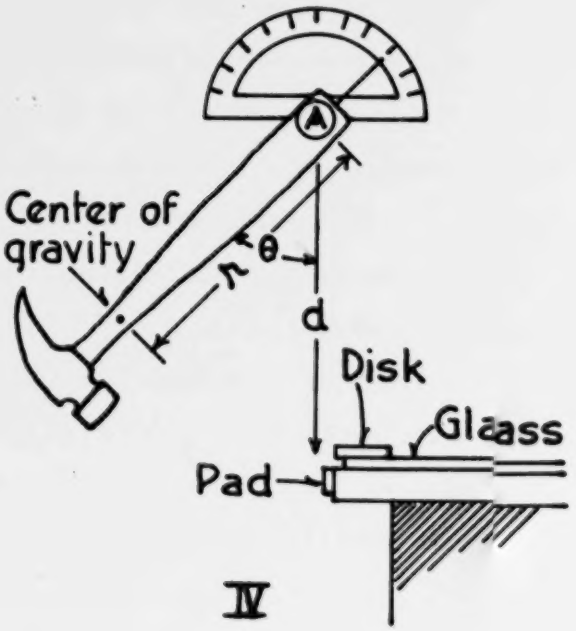
IV. CONSERVATION OF MOMENTUM

In the experiment to be described, principles from several areas of mechanics are applied to the solution of a single situation. While the emphasis is on conservation of momentum, we also use ideas related to energy, rotational motion, oscillation, and friction. The procedures and results have implications not only for the behavior of macroscopic objects, but also for atomic and molecular events.

In brief, a hammer is allowed to swing horizontally against a metal disk resting on the edge of the table. The disk slides across the table surface with a measurable and reproducible initial velocity. If desired, the study can be stopped profitably at this point since measurements of the distance the disk moves before stopping and the coefficient of friction can yield another measure of the disk's starting speed with which the calculation can be compared. However, the moving disk can be used as a projectile to strike other disks on the table top thus permitting us to set up various impact situations with measurable angles and velocities.

A hammer is pivoted near the end of its handle as in diagram IV. A hole drilled through the handle can accommodate a thin triangular file used as a knife-edge. The height and position of the support are such that the center of the face of the hammer comes just to the edge of the table surface when it hangs freely. The support also bears a protractor on which a pointer from the end of the hammer handle indicates the angle through which the hammer is to fall. The edge of the table can be

protected by a pad (a couple of Bandaids will serve the purposse). A plate of glass positioned just inside the table edge gives a uniform surface on which the disk can slide. A coin or washer can be used for the disk. A meter stick and stopwatch are also needed.



When the hammer is drawn back and released, it reaches the lowest point of its swing with a kinetic energy equal to the work done in pulling it back, or:

$$\frac{1}{2} I\omega^2 = Mgh$$
$$= Mg(r - 4 \cos \theta)$$

where I is the moment of inertia of the hammer around its pivot, ω is the angular velocity at the bottom of its swing, M is its mass, g the acceleration of gravity, r the distance between the pivot and the center of gravity of the hammer and θ the angle through which it was initially displaced.

The velocity with which the hammer head strikes the disk is given by $V = \omega d$, and after substituting in the energy equation and simplifying, we have:

$$V = d\sqrt{\frac{2Mgr\ (1 - \cos \theta)}{I}}$$

Now, assuming the collision of the hammer and the disk to be perfectly elastic, we can write the statement for the conservation of differences of velocities as: $V - 0 = v - V^1$, where v is the velocity of the disk, and V^1 the velocity of the hammer head after the impact. Since the hammer head is very massive in comparison with the disk, we can take $V = V^1$, so that $v = 2V$, or:

$$v = 2d \sqrt{2Mgr \frac{(1 - \cos \theta)}{I}}$$

If the hammer is allowed to swing freely as a physical pendulum, its period T will be given by:

$$T = 2\pi \sqrt{\frac{I}{Mgr}}$$

from which:

$$I = \frac{T^2 Mgr}{4\pi^2}$$

and using this expression in the equation for the velocity of the disk we have:

$$v = \frac{4\pi d}{T} \sqrt{2(1 - \cos \theta)}$$

Since the disk is decelerated by friction, it will slide a distance s across the surface which is:

$$s = \frac{v^2}{2a} = \frac{v^2}{2\mu g}$$

or

$$v = \sqrt{2\mu sg}$$

in which μ represents the coefficient of friction.

Results of these two independent determinations of the disk's initial velocity can thus be compared. This comparison can be made for a variety of angles. As indicated by the theory, a graph of v^2 against the quantity $(1 - \cos \theta)$ should be linear.

It is important to make a careful measurement of the angle. It helps to mount a rigid stop behind the hammer handle so that in a series of trials it is always brought back to the same position. The coefficient of friction between the disk and the surface can be measured by tilting the glass plate, measuring the angle for which the disk slides uniformly and using the knowledge that the tangent of this angle is equal to the coefficient of friction.

Since the collision is not perfectly elastic, and we have a way of measuring the two important velocities, the reasonable assumption can be made that the velocity of the hammerhead is the same after as before the impact, and the coefficient of restitution can be calculated.

If it is desired to study impacts between disks, the initial position of the target disk, and the final positions of both disks can be marked. Measurements of the distances they travel from the collision can be used to find their velocities. Taken with measurements of the angles of their paths these can lead to vector diagrams showing conservation of momentum in the encounter.

If chalk dust is lightly sprinkled over the glass plate, the paths of both particles are shown before and after the collision.

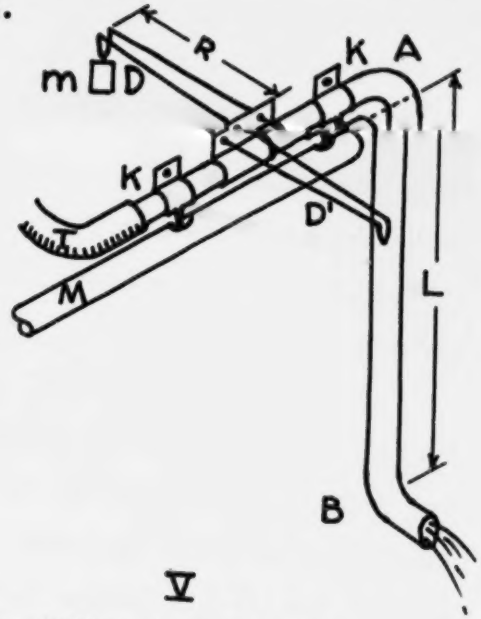
V. IMPULSE OF A WATER JET

The laws of motion in general, and fluid flow in particular, and the law of Conservation of Momentum are well illustrated in the experiment to be described. A bent piece of tubing is suspended so that when it delivers a stream of water the reactive force caused by the water making the turn results in a torque. This torque is balanced by an opposite torque supplied by hanging weights. The relationship (the equality of moments) describing the situation is thus:

$$mgR = \frac{Mv}{t} L$$

in which mg is the weight supplying the balancing torque, and R is its lever arm, M is the mass of water delivered in time t, v its velocity and L its lever arm.

The central piece of apparatus can be made of glass tubing, as shown in diagram V, or even more simply, of copper or brass tube. The tubing is given two right angle bends at A and B in planes which are mutually perpendicular. It is supported on points or knife-edges so that it can swing very freely. The diagram shows these supports at KK. If glass tubing is used, they may be sharpened screws, soldered to the undersides of small clamps made of sheet brass. If brass or copper tubing is used,



V

the screws can be soldered directly to the tubing. R is a horizontally mounted support rod, in which two shallow depressions have been drilled for the sharpened screws to rest in. Water is fed into the apparatus by rubber tubing T. Another sheet brass clamp C has similar arms of stiff wire DD' extending out on both sides. The weights for balancing the torques are hung as shown at m.

The apparatus is assembled and aligned. In all measurements arm AB of the tube will be in the same position. This may be judged by sighting past it toward some fixed vertical edge, or for greater precision, a small mirror could be mounted on the horizontal section of the tube, and the reflection of a scale used to regain the same position. At the start, small pieces of copper wire are pinched on the arms DD', as needed to make tube AB line up with the reference line. Note that since the apparatus is always in the same position while measurements are being made, the torque due to the rubber tubing is always the same, and is balanced out in this initial adjustment.

A small weight, 1 gm., is hung on arm D. The water is turned on cautiously and its flow adjusted until AB returns to its initial position. If the water pressure fluctuates frequently, a constant pressure tank will be needed to supply water. The flow of water for each setting should be reasonably constant for a minute or two while readings are being taken. Water from the tube is caught in a beaker for a definite time to obtain the rate of flow.

The velocity of the water stream can be obtained in two ways. If we know the rate at which water is being delivered, and the radius of the tube, we can state that:

$$M = \rho V = \rho \pi r^2 v t$$

or

$$v = \frac{M}{\pi \rho r^2 t}$$

where v is the velocity, M is the mass of water delivered in time, t, r is the radius of the delivery tube, and ρ the density of water. The original torque equation then becomes:

$$(1) \quad mgR = \frac{LM^2}{\pi \rho r^2 t^2}$$

Since the radius of the tube is small, and it is squared in the relationship being investigated, this measurement must be made with great care.

In a second method of measuring the water velocity the apparatus is mounted high enough above the sink so that measurements can be made on the trajectory of the water stream. If the water is discharged in a horizontal direction and then falls a vertical height y while moving a horizontal distance x in the same time, we can equate the expressions for the time:

$$\frac{x}{v} = \sqrt{\frac{2y}{g}}$$

or

$$v = x\sqrt{\frac{g}{2y}}$$

The torque equation thus becomes:

$$(2) \quad mgR = \frac{MLx}{t}\sqrt{\frac{g}{2y}}$$

As indicated by equation (1), even though concealed by equation (2), the reactive force of a water jet is proportional to the square of the rate of flow of water, and a graph of $\left(\frac{M}{t}\right)^2$ ploted against $\frac{mgR}{L}$ will show this.

VI. CENTRIPETAL FORCE

As a pendulum swings, the tension in its supporting cord must, in addition to supporting the weight of the bob, supply the centripetal force which causes it to follow a curved path. At the lowest point in the arc the cord tension is:

$$F = mg + \frac{mv^2}{r}$$

where m is the mass of the pendulum bob, v its linear velocity at that point and r the length of the pendulum. We can also state that at this point the bob's kinetic energy must be the same as its potential energy at the highest point of its swing:

$$\tfrac{1}{2} mv^2 = mgh \text{ or, } v^2 = 2gh$$

in which h is the height of the end of the pendulum's arc above the lowest point. Combining this with the first statement, we have:

$$F = mg + \frac{2mgh}{r}$$

$$= mg \left(1 + \frac{2h}{r}\right)$$

In the experiment to be described the quantities in this expression are measured directly.

Measurement of the factors in the right hand side of the equation is easily done with meter stick and balance. Measuring the tension in the pendulum cord presents the problem. A crude and rather unsatisfactory result can be obtained by simply including a spring balance at the pendulum support, and taking readings "on the fly."

A much better method permits readings consistently within 2 percent of agreement. It uses the usual low form of beam balance supported at the table edge on a rod as if for specific gravity measurements. The pendulum hangs from the hook under the pan and swings in a plane parallel to the table edge. A second vertical support rod is mounted beside the balance. On it are fastened horizontal rods which pass above and below the balance beam and limit its motion to perhaps 1/16 of an inch each side of its rest point. This prevents damage to the balance and also permits a very accurate determination of a condition of balance. A meter stick is also required.

After assembling the apparatus the balance is used to determine the mass of the pendulum bob, and the length of the pendulum is measured from the balance hook to the center of the bob. The balance is then adjusted for a weight perhaps 50 percent greater than the pendulum's weight and the pendulum is drawn aside and set in motion. By trial and error it is found from just how great a height the pendulum must be started in order to cause the balance beam barely to move. When this happens the tension in the cord (F) is given by the balance setting. The difference between this height and the height of the bob at the center of its path, both measured from the same reference level such as the floor or table edge, is used as h in the formula derived above.

If desired, the experiment can be broken down into a series of readings designed to show separately the relationship

between the centripetal force and the radius of the curve, the velocity and the mass, the other variables being kept constant.

Rather than presetting the balance and finding the appropriate height, as suggested above, it is also possible to lift the pendulum to a predetermined height, and adjust the balance.

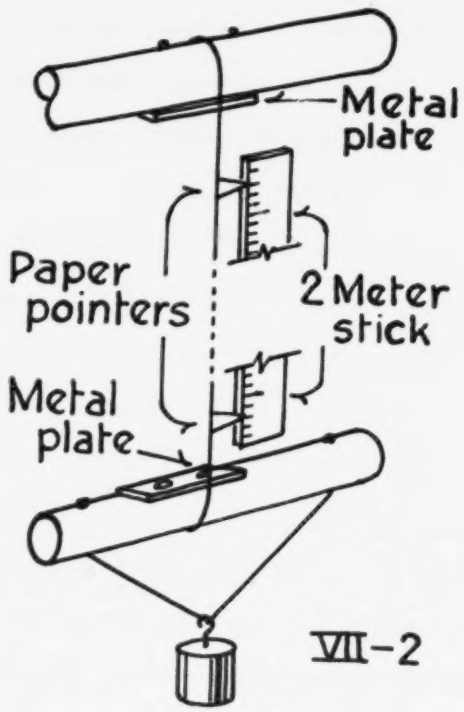
VII. YOUNG'S MODULUS, PLASTIC DEFORMATION AND FRACTURE

(1) The measurement of Young's Modulus is a standard classic in the physics laboratory. In its usual form the experiment consists in hanging weights on the end of a long piece of wire of the test material, measuring its elongation under increasing stress, and from its known length and a graph of change of length against stress, calculating the desired modulus. Experimental details are given in most manuals and need not be repeated here. The two difficulties to be surmounted are the yielding of the support and measurement of the rather small change of length. The first is solved by using an extremely sturdy support or by making all length measurements from the support, not from floor, table or other reference point. The second requires using a great length of wire so that the change in length will be large enough to be directly measurable, or an optical or mechanical lever of which there are several versions listed in science supply company catalogs.

(2) It is possible to investigate several basic concepts in addition to that of Young's Modulus by using copper wire as the test material. Its elastic limit is very easily exceeded and from this point on it undergoes plastic deformation. The decrease in diameter can be easily measured. The phenomenon of creep introduces a time factor in the experiment and after the wire breaks, the constriction at the point of fracture can be observed and a measurement of tensile strength is possible. Annealing the wire with a bunsen flame changes its characteristics

markedly and offers an interesting opportunity for further study.

The experimental problem here is that of clamping the ends of the wire without deforming and weakening it at these points. Two clamps can be made out of pieces of broomstick. Each has a rigid metal plate fastened to it by machine screws which pass through the wood. The testwire is passed under the plate which is then tightened. The wire then passes 3/4 of the way around the wood. The result is that friction between the wire and the wood supports much of the wire tension and the wire is not appreciably strained at the clamps. The lower clamp has a weight hanger attached as shown in diagram VII-2 . The upper one is long enough to be held by a standard right angle clamp attached to a ceiling support. Paper pointers are cemented or taped to the wire about 150 cm. apart and a 200-cm. rule is separately mounted so that their positions can be read (NO. 24 copper wire is suitable). A micrometer caliper and a set of large weights are also needed.



VII-2

The experimental procedure is evident from the preceding discussion. Since the elastic limit is very easily exceeded, great care must be taken with the first measurements (using weights up to about a kilogram) so that a value for Young's Modulus can be obtained. The breaking strength for the wire suggested is about 5 kg. The total change in length at this point will be something like 35 cm. so that the bottom of the weight hangar should be somewhat more than this distance above the floor at the start. A pad of rags under it will prevent damage to the floor when the wire breaks.

(3) It is possible to make a very instructive measurement of Young's Modulus by using the fact that the velocity of longitudinal waves in a solid material is given by:

$$v = \sqrt{\frac{Y}{\rho}}$$

where v is the velocity, Y is Young's Modulus and ρ is the density of the medium. A rod of the test material (coefficient of linear expansion rods are suitable) is clamped at the middle and stroked lengthwise to induce longitudinal vibration. The wavelength of the resulting vibration is then twice the length of the rod. The frequency can be determined by direct comparison with the output of a variable frequency audio-oscillator. The velocity is then calculated from the frequency and the wavelength. The measurement of density offers no problems.

A better way of obtaining the frequency is to match it with the resonant frequency of a closed-end air column.

The rod is mounted vertically over the air column (the same apparatus usually used in the elementary laboratory for determining the velocity of sound in air). The length of the air column is then varied while the rod is in vibration and several resonant points should be observable. If the positions of the shortest and longest resonant air columns are taken, the distance between them can be divided by one more than the number of reinforcement points heard between them to find 1/2 the wave length of the sound in air. The frequency is then calculated from the wavelength and the velocity of sound in air after applying the usual corrections.

(4) Another method of measuring Young's Modulus requires the suspension of a very long piece of fine steel or brass wire in an open stair well or other clear vertical shaft. A large weight hanging on such a length of wire can be caused to bob up and down as if on the end of a much shorter coiled spring. The elastic constant is determined by applying the usual simple harmonic motion relationship after having measured the frequency and the mass. This is then used in the defining equation for Young's Modulus. The length of the wire can be found from a measurement of the period when the mass is allowed to swing as a simple pendulum.

VIII. SIMPLE HARMONIC MOTION

(1) The Compound Pendulum. As an experimental device the compound pendulum is too well-known and its theory too completely treated in texts to deserve extended discussion here. Certain experimental simplifications and details may, however, be worth outlining.

A swinging meter stick makes a satisfactory physical pendulum. A hole is drilled as near as possible to one end, and the stick can then be pivoted on a thin finishing nail passed through the hole. The period of a thin rod, oscillating this way can be shown to be given by:

$$T = 2\pi\sqrt{\frac{2L}{3g}}$$

where L is its length and g the acceleration of gravity.

If a mass is clamped to the meter stick at some point, it will, with the exception of one location, change the period. A C-clamp can serve satisfactorily as such an added mass. Knowing the mass and its location, and assuming it to be a point mass (not quite, but nearly true), the period can be predicted from the usual physical pendulum formula. The center of gravity of the combination can be found experimentally, or can be calculated. In the latter case, the period turns out to be:

$$T = 2\pi\sqrt{\frac{\frac{ML^2}{3} + Cd^2}{g\left(\frac{ML}{2} + Cd^2\right)}}$$

in which M is the mass of the meter stick, L its length, C the

mass of the added object and d its distance from the point of support.

An interesting problem can be posed by asking pupils to find at what point an added mass can be clamped without changing the period of the meter stick. A graph of the period against the position of the clamp will show a position for which the period is the same as that at the unloaded stick. The clamp can then be placed at that point to test the results. This question is equivalent to asking the length of a simple pendulum of the same period as the stick, thus:

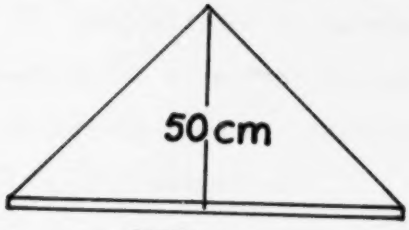
$$2\pi\sqrt{\frac{l}{g}} = 2\pi\sqrt{\frac{2L}{3g}}, \quad \text{or } l = \frac{2L}{3}$$

where l is the length of the simple pendulum and L is the length of the meter stick.

Another situation which is not generally known is brought about when a second meter stick is fastened rigidly at right angles to the first by a screw passing through their centers. The pendulum is now a plus sign oscillating in its own plane. The added mass can not now be considered a point mass, and thus the previous analysis does not apply. If the angle between the two sticks is changed from 90° to 0°, it is found that the period remains the same for all orientations and is the same as that of the unloaded meter stick. This might be anticipated when the sticks are aligned because we have then a rod of the same length but twice the thickness.

The part played by the second meter stick can be appreciated if it hangs separately by threads as shown in

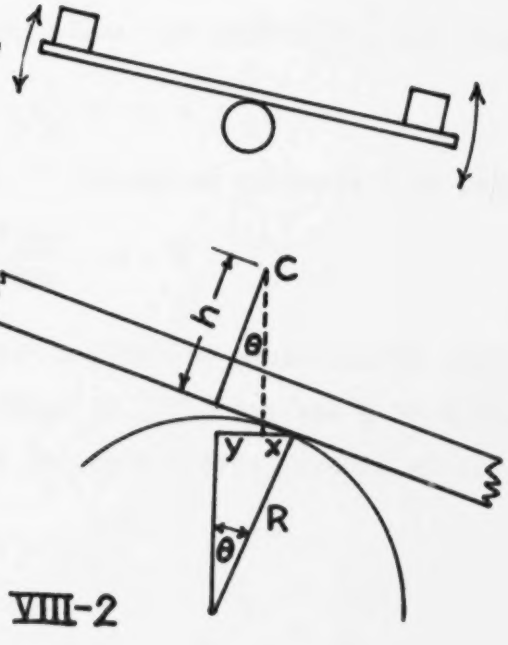
diagram VIII-1 . The lengths of the threads are such that the center of gravity of the stick is just 50 cm. below the support. If it oscillates in the plane of the threads, its period will be the same as if it hangs from one end. Changing the lengths of the threads so that the meter stick is no longer horizontal when at rest does not change the period provided that the center of gravity of the stick is always 50 cm. from the support. Thus mounting the second meter stick at the 50.cm. point of the first does not change the period.



VIII-1

If, however, our plus sign is allowed to swing in a plane at right angles to its own plane the added meter stick behaves approximately as a point mass.

(2) A situation which is simple physically, but fairly complex mathematically can be easily assembled. A meter stick, loaded with equal masses placed at equal distances from its center, is balanced on a cylindrical surface. If the center of gravity of the combination is not too high, it will rock after having been displaced with nearly simple harmonic motion. The positions and magnitudes of the masses and the radius of the



VIII-2

supporting cylinder can be varied, to study their influence on the period of oscillation. Since the moment of inertia can easily be varied through a large range, this experiment should serve well to clarify the part played by moment of inertia in oscillation.

In diagram VIII-2 the vibrating system has rotated through angle θ. Its mass is M and its center of gravity is at C, located at height h above the point at which the stick touches the cylinder when at rest. The restoring torque is seen to be:

$$L = Mgx$$

Now $x + y$ is approximately equal to $R\,\theta$, and y is approximately equal to $h\,\theta$, so:

$$x = R\,\theta - h\,\theta$$

and consequently:

$$L = Mg\,\theta\,(R - h)$$

Since the restoring torque is proportional to the angular displacement the motion must be simple harmonic and its period is:

$$T = 2\pi\sqrt{\frac{I}{Mg(R - h)}}$$

When this equation is solved for R we get:

$$R = h + \frac{4\pi^2 I}{MgT^2}$$

Thus, if cylinders of varying radius are used as the support, a graph of R against $1/T^2$, or against the square of the frequency, will be linear, with a slope of $4\pi^2 I/Mg$, and an intercept of h.

If the combined moment of inertia is broken down into the moment of inertia of the meter stick and that of the weights, the period becomes:

$$T = 2\pi\sqrt{\frac{I_o + 2mr^2}{Mg(R - h)}}$$

in which I_o is the moment of inertia of the meter stick, m the mass of one of the added masses and r its distance from the center of the meter stick. When this is solved for r^2, we have

$$r^2 = T^2 \frac{Mg(R - h)}{8\pi^2 m} - \frac{I_o}{2m}$$

This shows that a linear relationship exists between the square of the period and the square of the distances at which the masses are placed on the stick. For very large masses, say 500 gm. each, the constant term is small, and a plot of T against r will also be reasonably linear.

Needed are a meter stick, several pairs of equal masses, a stopwatch and a variety of smooth cylindrical supports. Large cylindrical weights, beakers and jars of various sizes will serve as the supporting cylinders. They should be clamped so that they remain stationary while in use.

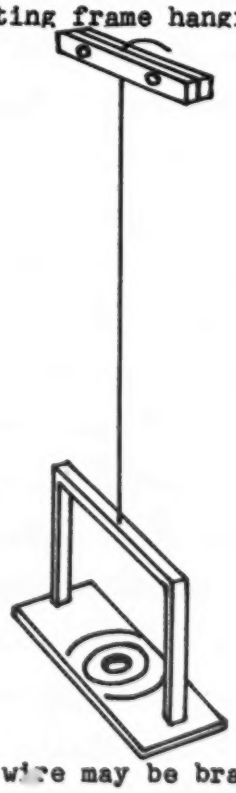
The procedure is straightforward and depends upon the goal set for the experiment. Perhaps a minimum quantitative study would be of the relationship between the period and the distances of the masses from the center. Going a step further, the pupil can study the effect of the radius of the cylinder on the period.

The heights of the center of gravity can be changed by attaching the masses to the underside of the meter stick. Note that if they hang from loops of string, the center of gravity shifts from side to side as the meter stick oscillates.

IX. THE TORSION BALANCE

This experiment has many desirable features. It illustrates a phenomenon fundamental to the operation of many instruments and also introduces a useful device. It relates the fields of rotation, vibratory motion and elasticity. The experimental work can be done at a variety of levels from the descriptive to a quantitative investigation requiring fairly complex computations. Because so many different variables are involved, the study can be expanded almost indefinitely. However, the necessary apparatus can be devised and put in operation quite easily.

The basic item of equipment is a supporting frame hanging from a length of wire. One form is shown in diagram IX. It should be rigid, but light, and strong enough to support two or three kilograms. Its dimensions are unimportant but something of the order of 6 inches square is appropriate. It is important that the wire be rigidly attached at the center of the cross member and that the center of the platform be marked. A hole at this point will serve to seat spherical objects and a series of concentric circles will help to locate other bodies such as rods and cylinders. The wire may be brass or steel of almost any convenient length and diameter, and rigidly held at the top. When set into oscillation the frequency will



IX

depend inversely on the length and directly on the square of the diameter of the wire. In addition to this torsion balance, the experiment requires some uniform objects; spheres, cylinders, rings and rods. A stopwatch and meter stick are also needed. If the effect of the supporting wire is to be studied, a micrometer caliper is required.

When the frame is rotated about its center it twists the wire and this brings about a restoring torque (L) which is proportional to the angular displacement, or:

$$L = K\theta$$

The constant K is analogous to the spring constant when a spring is stretched. When the frame is released, it vibrates with simple angular harmonic motion and its period T is given by:

$$T = 2\pi\sqrt{\frac{I_o}{K}}$$

I_o being the moment of inertia. If an object is supported by the frame the moment of inertia is the sum of I_o and the moment of inertia of the object. The moment of inertia of the frame can be neglected if it is much less than that of the body.

Center a light stick, such as a meter stick, on the frame. Set equal masses, perhaps 500 gm. each, on the stick at equal distances from the center. If they are not too close to the center they may be treated as point masses and the added moment of inertia will be $2mr^2$. Get readings of the period for various radii and plot a graph of the square of the period against this additional moment of inertia. This should

yield a straight line. The intercept on the T^2 axis can be interpreted as the square of the period of the unloaded frame and meter stick combination. This can be confirmed by measurement.

Since moment of inertia is always proportional to the square of the period:

$$\frac{I_A}{I + I_A} = \frac{T_A^2}{T^2}$$

where the subscript A is used to stand for the unloaded meter stick and frame. Thus I_A can be calculated, and computation of the torque constant K is possible.

Regular objects whose moments of inertia can be easily calculated from measurements of dimensions and mass can be placed on the platform. Measurements of their moments of inertia can then be compared with computed values.

It is also possible to measure the shear modulus (G) of the material of the supporting wire. Engineering physics books give the relationship for the angle through which a rod is twisted by a torque:

$$\theta = \frac{2L_1}{\pi r^4 G}$$

where L is the torque, θ the angle of twist, 1 the length and r the radius of the wire and G the shear modulus. Since:

$$\frac{L}{\theta} = K, \text{ and } K = 4\pi^2 \frac{I}{T^2}$$

the relationship becomes: $$G = \frac{8\pi 1I}{r^4 T^2}$$

The necessary measurements and computations may be made and the result compared with handbook values for G.

If desired, the relationship $T \propto 1/r^2$ can be studied by using various supporting wires of the same material and length but different radii, or the proportionality between T^2 and l can be established by using different lengths of the same wire.

X. NEWTON'S LAW OF COOLING

For a numerous and important group of physical phenomena the relationship is exponential. In other words, the rate at which some quantity changes depends directly on the magnitude of the quantity. The time rate at which a radioactive material decays depends upon the amount of material. The "space rate" at which the intensity of radiation decreases as it passes through absorbing material becomes less as the intensity becomes less. The rate of change of voltage across a discharging capacitor depends directly on the voltage. The rate of change of the temperature of a cooling object depends on the difference between its temperature and that of its environment. This last statement is known as Newton's Law of Cooling and may be written:

$$\frac{dT}{dt} = -k(T - T_o)$$

where T is the temperature, t the time and T_o the temperature of the surroundings. The constant k depends upon certain features of the object. It must be directly related to the surface area of the cooling body, and to a constant we shall designate as L which has to do with the ability of the surface to lose heat and it must be inversely related to the heat capacity, C of the object, or by proper selection of units: $k = \frac{LA}{C}$

Thus, we can write: $\left[\frac{dT}{dt} = -\frac{LA}{C}(T - T_o)\right]$

which is transformed by integration to:

$$\ln(T - T_o) = -\frac{LA}{C}t + b$$

This is the equation of a straight line when $\ln(T - T_o)$ is plotted against time and the line has the slope $\frac{LA}{C}$.

The extent to which this situation can be developed by analysis in class and laboratory depends on the pupils' mathematics background. However, even those who cannot follow the derivation can acquire a "feel" for an exponential relationship, can learn the basic facts and can gain experience in plotting a logarithmic graph.

In the derivation of Newton's Law of Cooling, which starts from the Stefan-Boltzmann Law, it is necessary to make the assumption that the difference in temperature between the object and its surroundings is small compared to the absolute temperature. Thus the experimental check must be confined to a limited temperature range.

The details of apparatus and procedure are extremely simple and subject to an almost unlimited number of variations. In its most rudimentary form, a covered container of warm water is allowed to cool, its temperature being taken periodically. The original temperature of the water should be no more than 30 centigrade degrees higher than room temperature. Whether the liquid is stirred before each reading is not as important as making all readings in exactly the same way. The duration of the experiment depends on the time available, and the patience of the experimenter. After the first 15 minutes or so, when the cooling rate has decreased, observations may be made less often and the organization and plotting of data may be started.

The most elementary confirmation of the law is obtained by showing that the ratio of the rate of cooling to the temperature difference is constant. This can be worked out in tabular form or by graph. The logarithmic graph suggested above may be drawn by using log tables and plotting on ordinary graph paper or by direct plotting on semi-log paper.

If two identical containers are given different surface treatments, using paper or paint, their "heat loss constants" (L in the last equation) can be compared. This does not lengthen the experiment unduly because the two sets of readings can be taken alternately over the same periods of time.

It is also possible to make a direct measurement of the rate of loss of heat at a given temperature. An electric heater is used to hold the temperature of the substance constant. When this condition is achieved, the rate of loss of energy in the form of heat must be the same as the power at which the heater is being operated, a quantity easily evaluated by voltmeter and ammeter readings. Since:

$$\frac{dQ}{dt} = LA(T - T_o)$$

where $\frac{dQ}{dt}$ is the rate of loss of heat, this gives another way of evaluating L.

XI. HEAT OF VAPORIZATION OF WATER

Measurement of the heat of vaporization of water is probably the most challenging experiment of the usual elementary laboratory course. Students who have made the measurement by the method of mixtures will perhaps remember it as a frustrating experience and be intrigued by the thought that the major source of error, heat losses, can be practically eliminated by use of a different technique. In the experiment to be described, steam is generated by an electric heater, condensed, and caught for weighing. The situation can be described by the relationship:

$$LW_1 = 0.24E_1I_1t - Ht$$

in which L is the heat of vaporization, W_1 is the weight of steam in grams, E_1 is the voltage, I_1 the current in amperes, t the time in seconds and H the rate at which heat is lost to the surroundings.

The experiment is then performed again at a different level, but for the same time interval, thus:

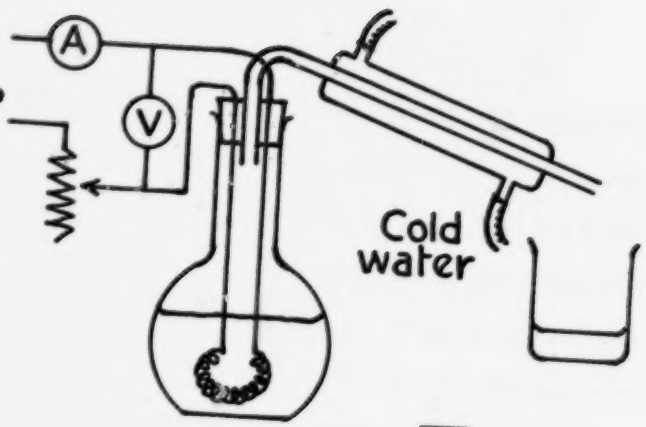
$$LW_2 = 0.24E_2I_2t - Ht$$

Since the temperatures of the equipment are the same in both cases, the rate of loss of heat is the same. Subtracting the two equations drops this term, and the result is

$$L = \frac{0.24t(E_1I_1 - E_2I_2)}{W_1 - W_2}$$

and we have thus eliminated the greatest source of experimental error.

The apparatus is represented in diagram XI and, except for the heater, is standard. Specifications for the heater must depend upon the electric supply which is to be used and the meters which are available. If it is to be operated from the power line, it can be designed to work at levels up to four or five hundred watts. Thus, if the maximum supply is to be 4 amperes at 120 volts, the resistance should be 30 ohms. It may be wound of No. 30 nichrome wire. The leads through the stopper should be of brass rod or heavy copper wire. The heater wire can be attached by bending the end of the lead around a small brass machine screw, then holding the resistance wire tightly between washers on the screw. Note that a heater of this sort should not be operated unless immersed in water. A bank of storage batteries is satisfactory as a source, using a lower resistance heater and supplying heat more slowly, but the unfiltered output of a rectifier is not, because of the effect of the wave-form on meter readings. The meters should be the best available.



XI

After assembling and testing the apparatus the water in the flask is heated to the boiling point by a bunsen burner which is then removed. Boiling is maintained by the electric

heater. Allow several minutes for the rate of production of distillate to stabilize before collecting it. Each experimental run should last at least 5 minutes to reduce errors involved in collecting and weighing the condensed steam. The water level in the flask must not be allowed to get lower than the level of any part of the heater.

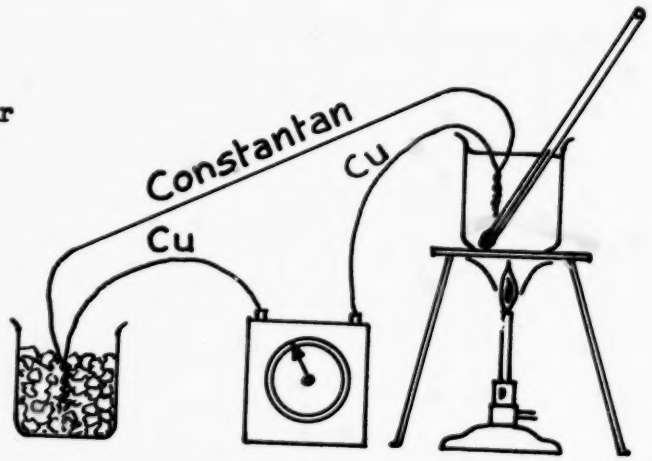
Periodic voltage and current readings are taken so that an average can be used if there have been any power supply fluctuations. If, while in operation, removing the voltmeter causes a readable change in ammeter deflection, the ammeter reading must be corrected for the voltmeter current.

XII. CALIBRATION AND USE OF A THERMOCOUPLE

This experiment introduces the student to the measurement of temperature by a thermocouple and reviews some elementary features of the phenomena associated with change of state.

The response of a thermocouple to a temperature difference between its junctions is not linear although it may appear to be so over a small range. One of the most interesting features of this experiment is the extrapolation of a calibration curve by mathematical or other means to a point quite far removed from the calibrating measurements.

A copper-constantan thermocouple is prepared by twisting together the ends of a 2- or 3-foot length of copper wire with the ends of a similar piece of constantan wire. The copper wire is then cut near its center and a microammeter or galvanometer is inserted in series. To obtain the original calibrating information one junction is placed in a container of crushed ice, and the other in a beaker of water which can be heated. The temperature to be measured is that of the melting point of tin (232°C). The tin is placed in a small crucible and substituted for the beaker of water. Diagram XII illustrates the apparatus.



XII

The actual handling of apparatus is quite straightforward. The only experimental pitfall arises from the possibility of shorts between the two wires which may occur at points other than where the temperatures are being observed. These are easily avoided. Electrical contacts in all parts of the circuit must be very secure. The melting point of the tin is found by allowing it to cool from a molten to a solid state and reading the current at regular intervals. The plateau in the curve occurs when the tin is giving up its heat of fusion and identifies the melting point quite precisely.

The first set of readings, taken with the hot junction in water yields a calibration curve which appears to be nearly straight for the range 0°C to 100°C. To find the melting point of the tin this range must be considerably extended. Making the assumption that the original line was straight leads to considerable error.

One approach to the problem makes the assumption (nearly true) that the curve is parabolic with its axis parallel to the current axis of the graph, and so has the form:

$$i = aT^2 + bT + c$$

where i is the current, T the temperature and a, b and c are constants to be evaluated. The origin and two other points on the curve are then used in this hypothesized relationship to find the values of the constants. With the equation of the curve thus known, the current at the melting point of tin can be substituted and the resulting equation solved for T.

A better method involves the conversion of the readings to millivolts so that they may be compared with handbook

data on the copper-constantan thermocouple. To do this, one must know the resistance of the circuit if readings are in microamperes, or if a galvanometer is used, it must be calibrated.

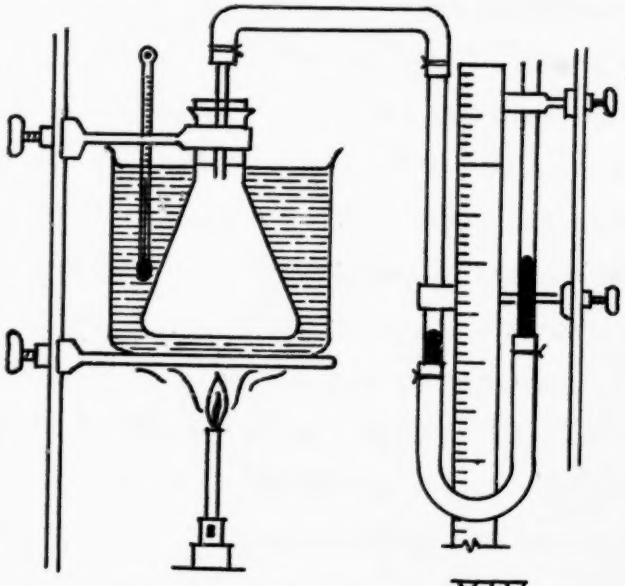
A simpler, but equivalent method is to assume the constancy of the resistance of the circuit (also assumed above and practically true) so that the ratio of the voltage to the current at one of the points in the calibrated range is the same as that ratio at the melting point of tin. The currents are taken from the data and the voltage at the lower temperature from the handbook. We can then solve for the thermal e.m.f. at the melting point of tin and find its equivalent temperature from the handbook tables.

This experiment may be developed into a long-term study. For instance, the peculiarities of the iron-copper thermocouple are interesting and shed a good deal of light on the phenomenon in general. By using glycerine instead of water, and a high-range thermometer, the neutral point of this combination can be found at about 205°C. Known temperatures for drawing the curve could also be obtained by using various salts with melting points in the desired range.

After the calibration of the thermocouple has been mastered, it might be used for a study of the freezing of an alloy, say, that of lead and tin. The unusual shape of the cooling curve for different proportions of the elements and the eutectic point are interesting features.

XIII. THE PRESSURE COEFFICIENT OF AIR and ABSOLUTE ZERO

The gas laws and the concept of absolute zero have so basic a place in our knowledge of the ways of nature that there should be some firsthand laboratory contact with these ideas. Besides, there is a grandeur to the thought that we can "measure" absolute zero that even appeals to the least imaginative and makes this experiment particularly attractive.



XIII

It is possible to improvise a reasonably satisfactory gas thermometer from standard laboratory glassware. A dry pyrex flask, containing dry air, is connected by a short length of tubing to a mercury manometer. The manometer consists of two pieces of straight glass tubing connected by about a foot of rubber tubing. The two arms of the manometer are held by separate clamps; the clamp holding the open end being arranged so that its height is easily changed. All joints are greased with silicone grease and the rubber tubing connections are reinforced with a tight twist of wire. Diagram XIII shows the apparatus with the air chamber in a water bath, and a measuring scale between the manometer arms.

With the water bath at room temperature, or colder, the open end of the manometer is lowered until the mercury in both arms is at about the same level. The level in the side connected with the flask is marked by a piece of thread tied tightly around the glass. The pressure in the flask is now equal to atmospheric pressure plus the pressure caused by the difference in height of the two mercury surfaces. If the temperature of the water bath has been constant for a few minutes, the air is at that temperature. The water is now heated and after its temperature has risen 10 or 15 degrees the heating is stopped. In a few minutes the manometer will stop rising indicating that the air is at the same temperature as the water. The open end of the manometer is now raised until the mercury in the other side is at the level of the thread marker thus making sure that the air is at the same volume as at the start of the experiment. The pressure and temperature are again recorded. In the same manner further readings are taken at temperatures up to the boiling temperature. If desired, the hot water can be siphoned out of the bath and replaced with cold water to see if the starting conditions can be reproduced as a way of making sure that the system did not leak during the experiment.

When a pressure-temperature graph is drawn, it is linear, if all has gone well. The pressure coefficient of air is readily computed from the line. An extrapolation of the line to zero pressure yields the experimental value of absolute zero. The extrapolation is best performed mathematically, having drawn the graph only for the pressure and temperature ranges actually measured.

If the pressure-temperature graph is not linear, the readings were probably taken too quickly allowing insufficient time for the air to come to the same temperature as the water. In this case, it is likely that the first and last points are the most reliable and the line can be drawn between them. This is because the time taken in making initial adjustments at the start allows the temperature to stablize at the beginning; and at the end, the temperature of the water bath is rising slowly enough so that the air temperature can keep up with it fairly well.

The volume of the heated air is not quite constant in this experiment. In the first place, the glass of the flask expands as it is heated. Making the correction for this effect will challenge the best students. It is too small an error to influence the result. Another error is caused by the fact that the air in the tube leading to the manometer is not being heated. This effect can be reduced by using capillary glass tubing between the flask and the manometer. This error is also rather small.

If it is desired to extend the experiment, the flask can be filled with other dry gases, carbon dioxide or hydrogen, for example, or a small amount of water can be added to show the influence of its vapor pressure.

XIV. ADIABATIC EXPANSION AND THE SPECIFIC HEAT RATIO

(Clement and Desormes' Experiment)

The adiabatic behavior of gases is a topic which, in its details, is usually as new and unsuspected to the physics students as it is fundamental. It is most desirable to be able to make measurements in this field and to get a feeling for the mathematics which describes it. The experiment described provides a direct observation of an adiabatic effect. A quantity of air is permitted to expand adiabatically. From measurements of its pressure before and after the expansion, and that of the atmosphere, the ratio of the specific heat of air at constant pressure to its specific heat at constant volume is obtained. This ratio is the exponent γ of the adiabatic equation:

$$PV^{\gamma} = k$$

The gas is originally at room temperature T_r at volume V_1 and some pressure P_1 above atmospheric pressure. It is then allowed to expand suddenly to atmospheric pressure P_r and volume V_2 and consequently cools adiabatically to temperature T_o. The adiabatic equation above may be combined with the general gas law to yield an expression which describes this change as follows:

$$P_1 V_1^{\gamma} = P_r V_2^{\gamma} \text{ (adiabatic equation)} \qquad (1)$$

$$\frac{P_1V_1}{T_r} = \frac{P_rV_2}{T_o} \qquad \text{(general gas law)}$$

$$\frac{P_1V_1}{P_rV_2} = \frac{T_r}{T_o} \tag{2}$$

From equation (1) $$\left(\frac{V_1}{V_2}\right)^{\gamma} = \frac{P_r}{P_1} \tag{3}$$

$$\frac{V_1}{V_2} = \left(\frac{P_r}{P_1}\right)^{\frac{1}{\gamma}}$$

Substituting from equation (3) into equation (2)

$$\frac{P_1}{P_r}\left(\frac{P_r}{P_1}\right)^{\frac{1}{\gamma}} = \frac{T_r}{T_o}$$

$$\left(\frac{P_1}{P_r}\right)^{\gamma}\left(\frac{P_r}{P_1}\right) = \left(\frac{T_r}{T_o}\right)^{\gamma} \tag{4}$$

$$\left(\frac{P_1}{P_r}\right)^{\gamma-1} = \left(\frac{T_r}{T_o}\right)^{\gamma}$$

The volume of the gas is then held constant while it warms from T_o to T_r. In this process the pressure rises from P_r to some higher pressure P_2. This second change is described

by the relationship:

$$\frac{T_r}{T_o} = \frac{P_2}{P_r}$$

Substituting this value of $\frac{T_r}{T_o}$ into the expression for the first change, we have:

$$\left(\frac{P_1}{P_r}\right)^{\gamma-1} = \left(\frac{P_2}{P_r}\right)^{\gamma}$$

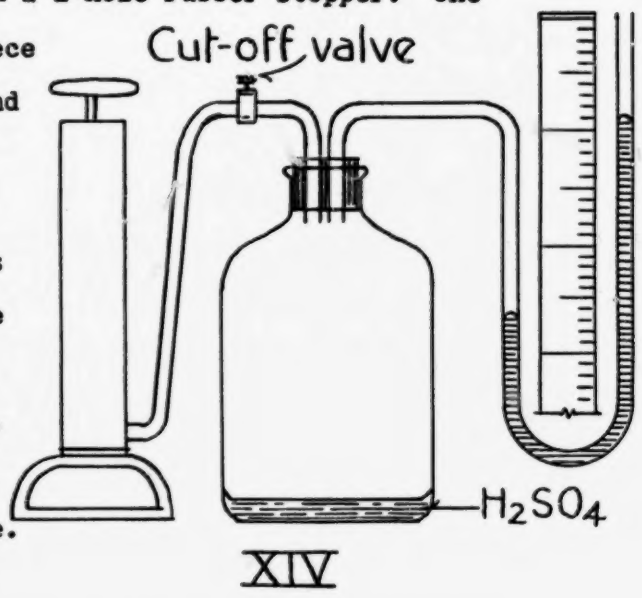
Taking logarithms:

$$(\gamma - 1)\ (\log P_1 - \log P_r) = \gamma(\log P_2 - \log P_r)$$

which reduces to:

$$\gamma = \frac{\log P_1 - \log P_r}{\log P_1 - \log P_2}$$

A 5-gallon carboy is used as the chamber for confining the gas. It is fitted with a 2-hole rubber stopper. One hole connects through a piece of rubber tubing with a hand pump (like a bicycle pump) which is used to raise the pressure. If the pump does not have a valve, a bicycle valve stem can be included in this part of the system. A good tubing clamp is required to close this tube. The other hole connects to a manometer containing either mercury or a nonvolatile oil. All joints are sealed with vacuum wax or silicone grease.



XIV

It is important that the air in the system be dry. To ensure this 100 $cm.^3$ or so of concentrated sulfuric acid is poured into the carboy before assembling the apparatus. Diagram XIV shows the apparatus used.

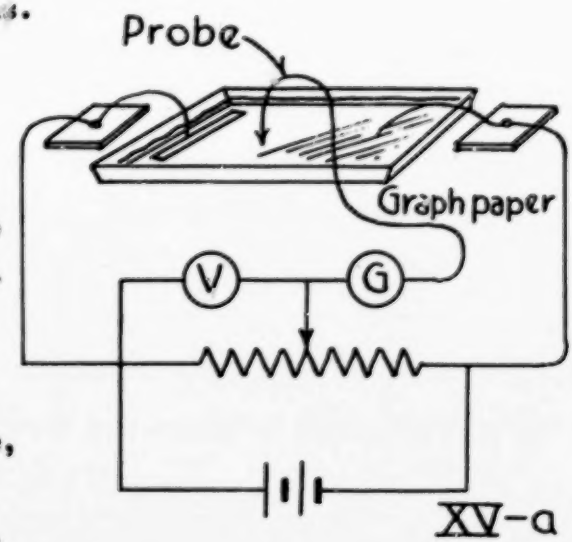
Using the pump, compress the gas until the manometer shows a pressure of 8 to 10 cm. of mercury above atmospheric. This warms the gas and after the valve has been closed the pressure will be observed to drop a little as the air cools to room temperature. After a few minutes the manometer indication stabilizes and it can be assumed that the gas has achieved room temperature. The absolute pressure at this point is taken as P_1. The stopper is then removed briefly, the gas expands to atmospheric pressure (P_r), and the stopper is replaced. This step should take no more than about 2 seconds. The gas which has cooled adiabatically now begins to warm to room temperature and the manometer shows a resulting gradual rise in pressure. When this change has ceased the gas temperature is again the same as that of the room and the final absolute pressure P_2 is taken. The value of γ is computed from these pressures as indicated above.

XV. THE ELECTRIC FIELD

Very effective devices for plotting electric fields are available commercially. However, the old-fashioned electrolytic sheet is easily set up, gives acceptable results, and can be adapted to the analysis in a great many situations.

Two electrodes dip into a thin sheet of electrolyte in a tray and a potential difference is established between them. Either a.c. or d.c. can be used. A certain potential within this range is selected and other points in the liquid at the same potential are located permitting the drawing of an equipotential line. Other equipotentials are found in the same manner and then the lines of force are drawn, always perpendicular to the equipotentials.

The basic piece of equipment is a clear glass refrigerator or dark-room tray that is large enough to cover a sheet of graph paper which is taped to its bottom. It contains a very shallow sheet of electrolyte, less than 0.5 cm. in depth. It must be carefully leveled.



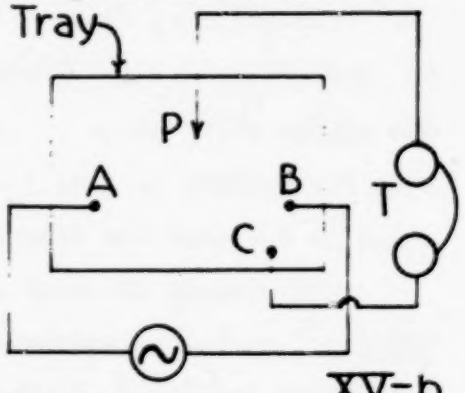
XV-a

The electrodes are attached to wood bases which stand on the table beside the tray. If d.c. is to be used, as indicated in diagram XV-a, the electrodes should be made of copper, and the electrolyte a dilute solution of copper sulfate, to prevent polarization of the "cell". A voltage divider is connected

across the source to set the potential to be investigated. When the probe is dipped into the solution at some point which has a different potential, the galvanometer deflects. The equipotential line is thus the line connecting points for which no galvanometer indication results. Data are conveniently taken on another sheet of graph paper. If the potential as indicated by the voltmeter is changed in equal steps, the separation of the equipotentials is an indication of the field strength.

The electrode may be of any shape desired. The pupil can plot the field between two points, between a point and a line (as shown in the diagram), between a circle and a point at its center (the Geiger counter tube) or any other situation that is real or imagined.

The experiment can also be done using an a.c. source which may be an audio oscillator or a low voltage transformer connected to the power line. In either case, the best null detector is an oscilloscope, but if the oscillator is employed earphones can be used.



XV-b

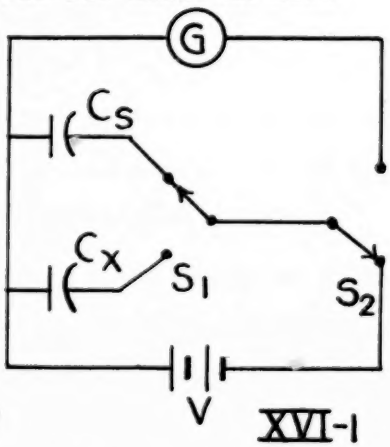
Instead of using the potentiometer to determine the potential being plotted, a third electrode can be added. Diagram XV-b shows the arrangement. A and B are the fixed electrodes. C is the electrode which is used to set the potential. P is the probe, T the earphones or oscilloscope and O the oscillator or other a.c. source. When a.c. is used the electrolyte can be tap water or if this is not sufficiently conductive, a small pinch of salt can be added.

XVI. CAPACITANCE

Measurement of capacitance may be done in a number of ways. The following procedures are suggested as illustrating fundamental concepts and being adaptable to simple laboratory equipment.

(1) Using a Ballistic Galvanometer. When a capacitor is discharged through a galvanometer the maximum needle deflection is proportional to the charge which passes through the instrument. At a given voltage this charge is proportional to the capacitance. Thus we can use a ballistic galvanometer to compare one capacitor with another which is taken as a standard by charging them to the same voltage and comparing the galvanometer throws when each is discharged through it.

The ordinary student-type, moving-coil galvanometer can be used ballistically. However, since its period is very short, the needle moves quickly, and therefore does not allow as much time for reading as does a galvanometer which is designed for this kind of use.



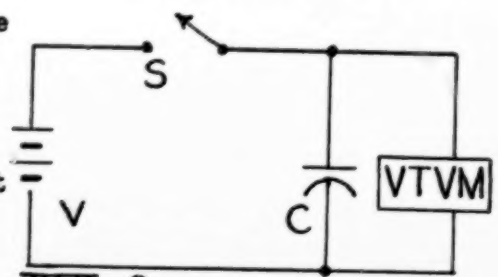
XVI-1

The circuit is shown in diagram XVI-1 , G is the galvanometer, C_s the "standard" capacitor, C_x the unknown, and V the voltage source. S_1 is a single pole, double throw switch , as is S_2. A toggle snap-switch is particularly useful for S_2, since its motion from one position to the other is quick enough to minimize the effect of leakage in the capacitor or its connections. The proper voltage is determined

by the capacitance and the characteristics of the galvanometer in such a manner that it is difficult to give specific values. It is suggested that, using about 2 mfd of capacitance, some rather low potential (1 v., for instance) be tried, and this then can be increased to a value which will produce a large, but safe meter deflection.

If the student is given one capacitor to use as a standard, and two others as unknowns, he can measure each of the unknown capacitances, and compare his results with the labels. Then he can measure series and parallel combinations and compare these results with those expected from theory.

(2) The Discharge Curve. If the laboratory contains a vacuum tube voltmeter it can be used to obtain the data needed to plot the exponential discharge curve of a capacitor. Such instruments often have a resistance of about 11 megohms so that when a 10 mfd capacitor is discharged through it almost 2 minutes are required for the voltage to drop to 37 percent (1/e) of the initial potential.



XVI-2

The scale used on the VTVM is chosen to be appropriate to the voltage source. After recording the voltage, the switch (diagram XVI-2) is opened and the voltage read periodically; perhaps every 10 seconds. A plot of the potential against time will be an exponential curve. Plotting the logarithm of the voltage against time should give a straight line. The time constant (T) can be read from these graphs as the time

required for the voltage to drop to 37 percent of its original value, and if the meter resistance (R) is known, the capacitance (C) can be computed from the relationship:

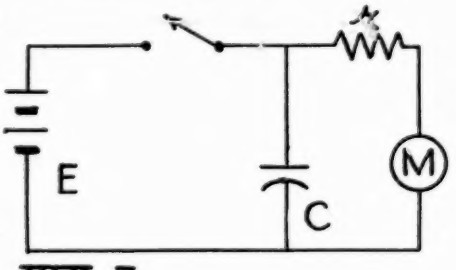
$$T = RC$$

Large capacitors are often greatly underrated by their labeled capacitance.

Other discharge curves can be easily obtained by using a different capacitance or by connecting a resistor of several megohms across the meter.

The usual 1,000 ohm/volt multimeter can be used instead of a VTVM if a very large capacitance is available and if the meter can be used on a high voltage range.

(3) Time Constant. The circuit shown in diagram XVI-3 will also permit measurement of time constant without a VTVM. It is essentially the same as that described in (2) except that here we improvise our high resistance voltmeter by placing a resistor in series with a sensitive milliameter or microammeter. The value of r is chosen so that when the switch is closed, applying the voltage, the meter M reads full scale, or nearly full scale. The more sensitive M and the greater E the larger r can be, and therefore the longer the time constant and the easier the timing operations. Typical values using a 0-200 microampere meter are E = 300 v., and r = 1.5 megohms.

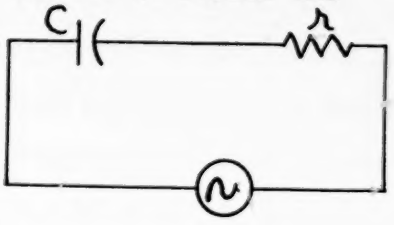


XVI-3

Unless C is quite large, it is probable that the discharge will be too quick to permit a series of readings from which a

graph can be drawn. However, the time constant can easily be measured for capacitors larger than about 1 mfd. Note the point on the meter scale at which the discharge current is just 37 percent of the initial current. Then, using a stopwatch, time the decrease of the current after the switch is opened until it has fallen to this level. The capacitance can then be calculated as suggested above.

(4) Capacitive Reactance. When a.c. is supplied to a circuit consisting of a capacitor and resistor in series the ratio of the voltage appearing across the capacitor (E_c) to the voltage across the resistor (E_r) will be the same as the ratio of the capacitive reactance (X_c) to the resistance (r), or:



$$\frac{X_c}{r} = \frac{E_c}{E_r}$$

Measuring these voltages and knowing the resistance permits evaluation of the capacitive reactance from which the capacitance may be calculated by:

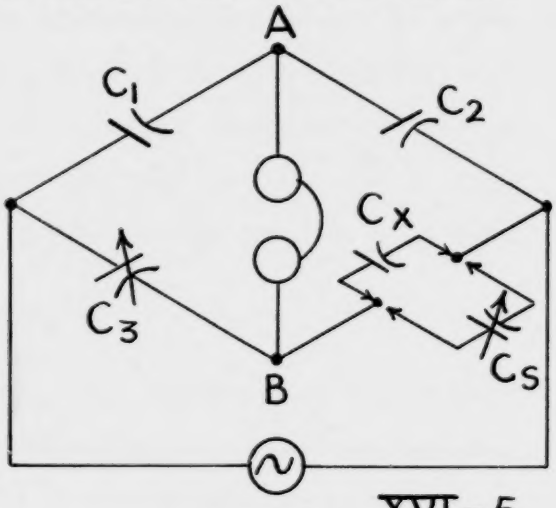
$$X_c = \frac{1}{2\pi fC}$$

where f is the frequency and C the capacitance.

The meter used for these voltage measurements should have high resistance. A vacuum tube voltmeter is best but a 1000 ohm per volt meter can be used. The source can be a low voltage transformer, or with proper safety precautions, the 115 volt line. The resistor should be chosen so that its resistance is comparable to the capacitive reactance. For example, 5,000 ohms is suitable for use with a 0.5 mfd capacitor.

A logical extension of the experiment is to work with the vector nature of the voltages measured, computing their vector sum and comparing it with the supply voltage. It is instructive to draw diagrams and make calculations for several different values of resistance with the same capacitor, or several different capacitors with the same resistor. The phase angle can be calculated, then measured with the method outlined.

(5) A Capacitance Bridge. Measure a capacitance by using it to balance an a.c. bridge, then substituting for it a variable calibrated capacitor and rebalancing the bridge (see diagram XVI-5). The unknown must have the same capacitance as the final setting of the standard. The voltage source for the bridge may be an audio generator or a low voltage transformer in the a.c. line. The balance indicator is preferably an oscilloscope but earphones may be used if the voltage originates in an audio oscillator. The standard (C_s) can be a decade capacitor or for small values, a radio tuning capacitor equipped with a good dial, and previously calibrated with a commercial capacitor bridge. C_3 is also variable and similar to C_s in range but need not be calibrated. It is used to balance the bridge when C_x is in the circuit. C_1 and C_2 are similar fixed capacitors of unimportant capacitance. The unknown, C_x, must lie in the range of C_s.

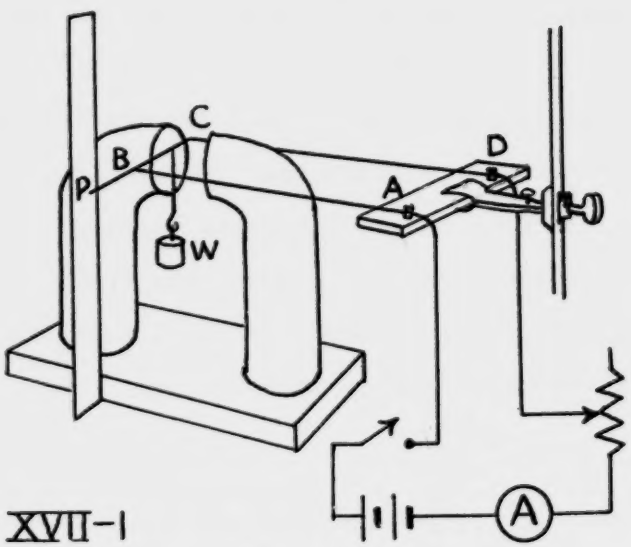


XVI-5

XVII. FLUX DENSITY OF MAGNET

(1) The flux density in a magnetic field may be defined in terms of the force on a moving charge. It is possible to determine this magnetic induction by directly measuring the force on a current carrying conductor in the field and using the relationship: $F = BIl$.

A strong magnet is needed for this experiment. Either a magnetron magnet, or a damping magnet from a kilowatt-hour meter will do. The current is passed through a long stirrup of nonmagnetic spring wire ABCD as shown in diagram XVII-1 . The open ends of the wire are attached to binding posts on an insulating block which is rigidly held in a clamp. The polarity of the source is such that the resulting force on segment BC of the wire is upward. A hook for weights, W, is attached to the center of BC and a wire pointer P extends from one end of BC to a fixed scale.



XVII-1

The rest point of P is first noted when there is no current in the wire. Then a small weight of 1 gm. is hung at W and the current adjusted to return P to its starting point.

This process is repeated for increasing weights. A graph of the force (W) against the current is linear and its slope is used to determine the force per unit current. Dividing this by the length of BC gives the average flux density over BC at that particular position in the magnet gap.

This prccedure can be repeated at various positions between the magnet poles to see how B varies from one side of the air gap to the other.

The sensitivity of the apparatus can be increased by increasing the length of legs AB and CD and by using wire of smaller diameter. The best ammeter available should be used.

(2) The snatch coil method of measuring flux density can also be used although it presents some experimental complexities. If a small coil attached to a ballistic galvanometer is suddenly moved from the region where the magnetic induction is to be measured to a region where the field is negligible, the charge which passes through the galvanometer and causes it to deflect is proportional to the induction. The relationship is:

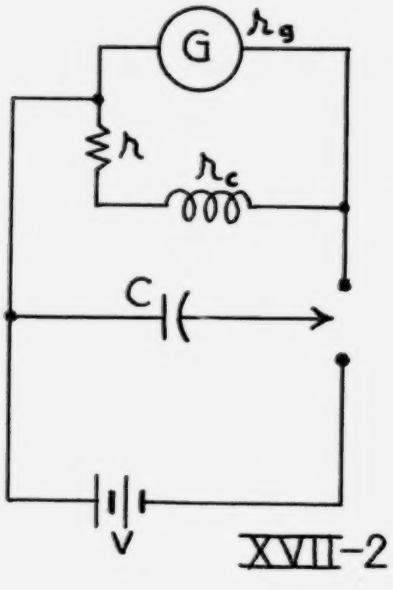
$$B = \frac{Rq}{NA}$$

where B is the induction, R the combined resistance of galvanometer and coil, q the charge, N the number of turns of the coil and A the area enclosed by the coil.

The galvanometer need not be one specially built for ballistic use. Any moving coil galvanometer of known resistance can be used, although, because of the speed of the deflection, it takes some practice to read the maximum "kick" on the usual laboratory instrument. The snatch coil may be 40 or 50 turns of

wire, held together by using the last turn to wrap the others. In order to calibrate the galvanometer a large capacitor of known capacitance is charged to a known voltage and then discharged through the meter. The sensitivity of the meter is determined by knowing the charge delivered by the capacitor and the resulting meter deflection.

Since the snatch coil damps the galvanometer it must also be connected when the meter is calibrated. However, since the coil resistance is low, it shunts the meter too much when the capacitor is being discharged through it. Therefore, a resistor r, comparable to the meter resistance is placed in series with the coil.



XVII-2

Connect the circuit as shown in diagram XVII-2. When the capacitor is discharged the portion of the original charge Q which passes through the meter is:

$$q = \frac{r + r_c}{r + r_c + r_g} \cdot Q$$

where r is the added resistor, r_c is the coil resistance (probably negligible), r_g the galvanometer resistance and Q the charge of the capacitor. If q is now divided by the meter deflection, we have a measure of the sensitivity of the meter

when used ballistically with r and the coil across its terminals.

The coil, in series with r and the meter, is now placed between the poles of the magnet being measured and suddenly removed. The resulting meter deflection is used with the previously measured sensitivity to give the charge q which is caused to flow. The radius of the coil is measured to determine its area and the magnetic flux density calculated from the equation stated above:

$$B = \frac{Rq}{NA}$$

Note: R is the sum of the resistances of the galvanometer, resistor and coil.

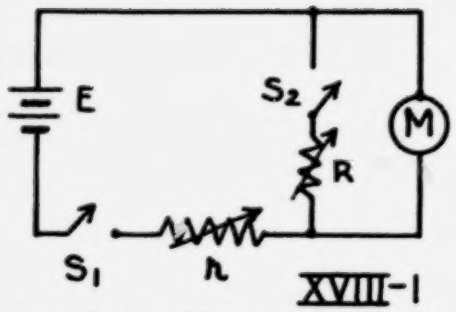
XVIII. SENSITIVE DC METERS

One of the well-known exercises of the electricity laboratory is the conversion of a sensitive meter to ammeter or voltmeter and the subsequent calibration of the device. The student is usually given a milliammeter with a range of 0 to 1 or 0 to 5 ma and having a known resistance. He then computes the multiplier which must be used to convert it to a voltmeter with some specified range, adds the multiplier and calibrates his instrument in an operating circuit against one which is accepted as a standard. To make an ammeter requires calculation of the shunt needed and the meter which results from adding a shunt wire of the proper resistance is again tested against another meter. Of the two problems producing an ammeter involves application of more physics and also considerably more hazard to the meter than making the voltmeter.

This experiment is straightforward and familiar but the initial determination of the resistance of the meter movement may be worth discussion. This could well be made a preliminary to the meter experiment; rather than being given the meter resistance, the pupil would start by measuring it. Or the determination of the meter resistance by one or more of the methods which follow could be the principal goal of the work.

(1) The meter is placed in a circuit with a large resistor and a voltage source. Since the meter resistance is much less than that of the resistor (r in diagram XVIII-1), it is assumed that a decrease of resistance in the part of the circuit including the meter would produce a negligible change

in the circuit current. In other words, shunting the meter with resistance R leaves the total current the same and therefore, decreases the meter indication.



XVIII-1

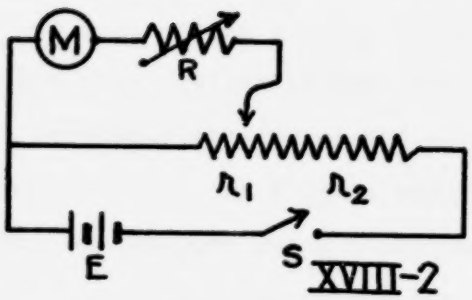
If the meter resistance is the same as R, we then know the meter resistance.

Typical values for a 0 to 1 ma movement are E = 4 v., and r = 5,000 ohms. R is a variable resistance box. After assembling the circuit, r is set at its maximum resistance and switch S_1 is closed. After reading the meter, S_2 is closed and R is adjusted to give half the original meter deflection. Its setting is then taken as the meter resistance. By changing r it is possible to make repeated trials using various initial currents. Instead of a calibrated resistance box as R, a rheostat can be used. After it is set for half deflection of the meter it is removed from the circuit and its resistance measured by conventional means.

Because the initial assumption that the current is constant is not quite true, this method gives a result which is a little smaller than the correct value.

(2) Given a source of constant voltage, doubling the resistance of a circuit results in reducing the current by half. This is the basis of a second "half-deflection" method of measuring galvanometer resistance. The circuit is shown in diagram XVIII-2 . Its accuracy depends on the portion of the potentiometer labeled r_1 being much less than the resistance

of the meter so that an increase in the resistance of the part of the circuit containing the meter produces a negligible change in the voltage across this parallel arrangement.



XVIII-2

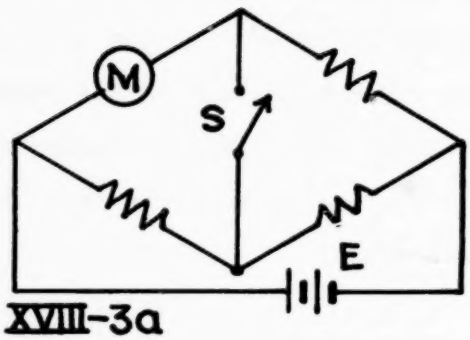
R is again a resistance box which includes the meter resistance in its range. Typically, E is 4 v., and r_1 and r_2 are portions of a 100 ohm variable resistor. With R and r_1 both at 0, the switch is closed. The contact on the potentiometer is then moved to increase r_1 producing a deflection of the meter. If R is now increased until the meter deflection is halved, it must be approximately the same as the resistance of the meter movement.

Since the voltage cannot remain quite constant during the adjustment, the final value of R will be slightly larger than the actual meter resistance.

The true meter resistance is the geometric mean of the values obtained by methods (1) and (2).

(3) The Kelvin bridge provides a method which does not depend for its result on an initial approximating assumption. The meter is used as one arm of a bridge. When the bridge is balanced closing the switch produces no change in the meter reading. Thus the usual relationship for a balanced bridge can be used for finding the meter resistance. When a slide-wire bridge is employed it is best to supply a rather small voltage so that R can be comparable to the meter resistance, and the balance point near the center of the wire. This is

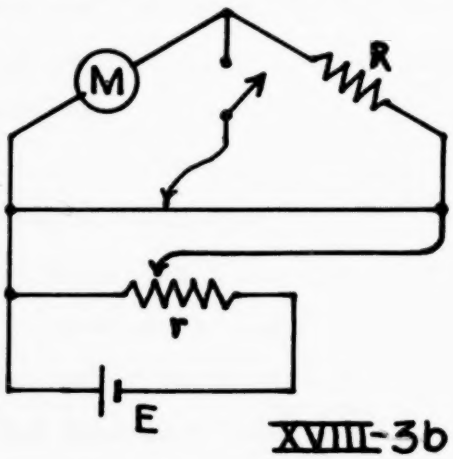
done by using a single cell to provide the potential labeled E and a 100 to 500 ohm potential divider at r. R is a resistor of accurately known resistance close to the estimated resistance of the meter. Employment of a variable resistance box permits a series of trials with different balance points. See diagram XVIII-3b.



XVIII-3a

If all three methods are used the result obtained in this third method should be very nearly the same as the geometric mean of the other two results.

(4) A slide wire potentiometer can be used in measuring the resistance of a galvanometer. A small voltage is established across the wire and the galvanometer cautiously connected to two points in the wire so that a deflection is obtained. A resistance box is now placed in series with the galvanometer and set at some value which is more than the galvanometer resistance. The contact points on the wire are now made exactly twice as far apart and the resistance of the standard is adjusted to give the same galvanometer reading. Then, since the voltage has been doubled, the current remaining the same, the resistance must have been doubled. Therefore, the galvanometer resistance must be the same as that of the variable resistor.



XVIII-3b

XIX. THE CATHODE RAY OSCILLOSCOPE

All serious students of physics should be able to operate an oscilloscope and should know some of its capabilities and limitations. The purpose of this account is to suggest a procedure for acquainting students with this valuable instrument. It is not likely that any one will want to perform all the exercises suggested, but the problems at hand and the availability of certain items of equipment will probably determine just how much is to be done.

(1) The Controls. In general, the panel controls of oscilloscopes are very similar in name and function. After learning what the various labels mean, and how to make the most elementary adjustments, a test signal can be supplied so that the functions of the amplitude, sweep frequency and synchronizing controls can be learned. The test signal from the panel binding post is not flexible and may be a little mysterious. The use of a small toy transformer or an audio generator is wise. Particular attention should be paid to the "synch" control and the student should practice making adjustments of the sweep frequency without using it.

(2) Nonlinearity of Sweep. Since the sweep voltage is part of the discharge curve of a capacitor, it is exponential rather than linear in most instruments. After aligning the coordinate screen with the sweep axis, a 60 c/sec. signal is viewed with the sweep frequency set as low as possible to show a whole number of waves. It is held stationary with a small amount of synch and the horizontal gain is set so that

the whole pattern is visible. The crowding of the waves at one end of the sweep should be evident. In order to show this graphically, the points where successive waves cross the axis in the same direction are read from the coordinate screen. Since these positions in the wave occur 1/60 sec. apart, a graph of the horizontal position (plotted vertically) against the time in 60th's of a second plotted horizontally will show the exponential nature of the sweep voltage change.

(3) Calibration of Sweep. The sweep dials can be calibrated against the frequency of the a.c. line. Viewing this alternating voltage with the synch control off, stationary patterns are formed when the sweep frequency has values which are multiples and submultiples of the line frequency. After the student has learned how to interpret these patterns, he may take data of dial settings against the revealed sweep frequency for the purpose of plotting a calibration graph. The data and graph can be extended by using a tuning fork as the standard and feeding its frequency to the oscilloscope through a microphone.

(4) The Oscilloscope as a Timing Device. The motion of the cathode ray spot on an oscilloscope screen is often used to time very rapidly repeated events of short duration. This may be illustrated simply. Connect a 10 ohm resistor in series with a buzzer and a suitable voltage source. The vertical input of the scope is then connected across the resistor. Since it "sees" the voltage across the resistor, the pattern must have the same form as the current in the circuit. The resulting figure reveals the closing of the

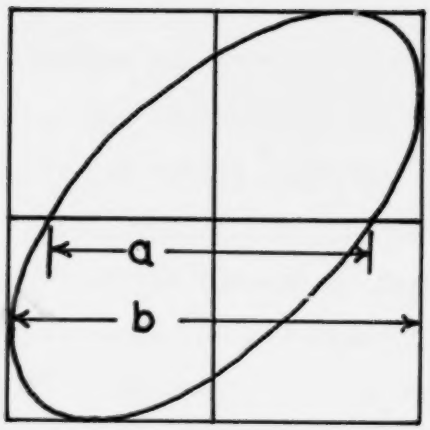
buzzer contact points (perhaps with some evidence of bouncing), the rise of current in the magnets of the buzzer and the opening of the circuit when the contact points separate. Now, referring to the sweep calibration curves of step 3, it is possible by making measurements on the coordinate grid in front of the tube to tell approximately how long the points stay closed, how long open and how long it takes the current to reach a maximum. Although we are ignoring the nonlinear nature of the sweep and also the fly-back time, these errors are not usually serious enough to make the experimental results invalid.

(5) Calibration of Vertical Gain Control. One of the major uses of the oscilloscope is as a voltage measuring device. When precision is a major goal this is usually done by direct comparison of the unknown alternating voltage with one which can be measured precisely by conventional means. A calibration curve for the vertical gain control can, however, serve well enough for most measurements. Data for this may be obtained by using a low voltage transformer as the source of the reference voltage and measuring its output with a reliable a.c. voltmeter. The voltage can be adjusted so that the full peak-to-peak wave is on the screen for various settings of the gain control and data taken so that a curve of sensitivity in coordinate units per RMS volt can be plotted against vertical gain setting. The horizontal sweep is off during this type of measurement. Note that for measuring voltages in waveforms which are not sinusoidal this curve must be revised in terms of peak or peak-to-peak voltages.

(6) Frequency Measurements. The calibrated sweep of step 3 permits rough measurements of frequency within the calibrated range. Accurate frequency measurements are usually made by forming Lissajou figures with the unknown frequency and one which is taken as a standard, such as the line frequency. Calibrating an audio oscillator is a good way to learn this technique. One of the signals is fed to the vertical input and the other to the horizontal input of the oscilloscope, the sweep being off. The variable frequency can then be adjusted to be nearly the same as the reference frequency and the typical "wobbling circle" pattern is seen. This pattern is worth studying for itself. Before leaving it the student should understand how it is formed, why it wobbles and the significance in terms of phase difference of the straight lines, circles and ellipses. When this has been mastered, the more complex patterns formed by multiples and fractions of the reference frequency are more easily understood. Oscillator dial settings which form stationary patterns and the frequency as shown by the shape of the figure form the data from which a calibration curve for the oscillator is drawn. As in step 3, this can be extended by using a higher known frequency as a standard, such as that of a good tuning fork.

(7) Phase Measurement. One can measure the phase difference between two sinusoidal signals of the same frequency by making them form a Lissajou figure. Center the pattern and adjust the vertical and horizontal gains so that the two signals produce deflections of exactly equal amplitude on the scope

screen. The ellipse or circle then fits into a square formed by the lines on the plastic coordinate screen of the scope, as shown in diagram XIX-7a. If the waves are exactly in or out of phase the straight line will be a diagonal of the square. When these conditions have been met the phase angle φ is given by:

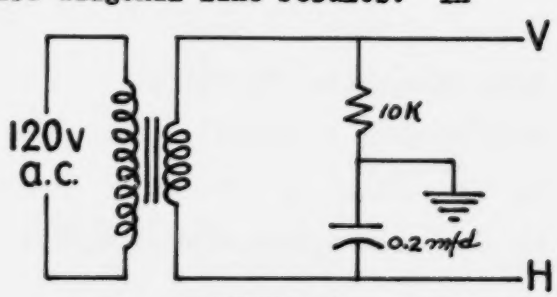


XIX-7a

$$\sin \varphi = \frac{a}{b}$$

where a is the distance between the intercepts on the x-axis and b is the total width of the figure.

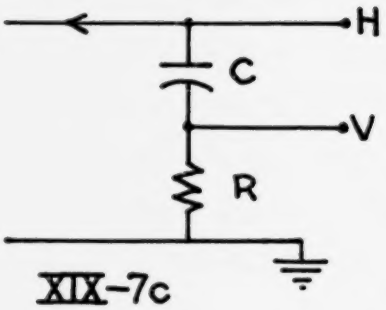
A low voltage transformer serves as the voltage source for this experiment. If it is first caused to supply the same signal to both axes, the in-phase diagonal line results. In order to see the 90° phase relationship circle a capacitor and resistor are connected to the transformer as shown in diagram XIX-7b. The values are not important and those indicated will serve. V and H are the vertical and horizontal terminals of the scope and the ground shown is connected with the scope's ground post. Since the vertical signal is the voltage across the resistor and is in phase with



XIX-7b

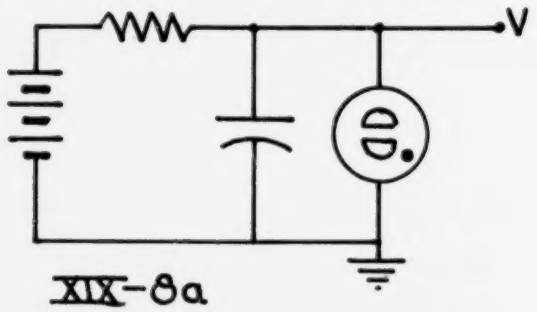
the current, it leads the voltage across the capacitor by 90°.

If the connections are now changed as shown in diagram XIX-7c, the phase difference between the voltage applied to the circuit, and the current in the circuit can be measured. A check can be made by computing the phase angle expected from the known values of resistance, capacitance and frequency. It is instructive to vary both capacitance and resistance and to make a series of calculations and measurements of phase angle.



XIX-7c

(8) Observation of Wave-Form. The obvious usefulness of the oscilloscope in showing the wave-form of various alternating voltages can be shown in a number of ways. A neon-tube relaxation oscillator will produce a sawtooth wave; its frequency being determined by the voltage and choice of components. The oscilloscope can be connected across the capacitor as indicated in diagram XIX-8a.

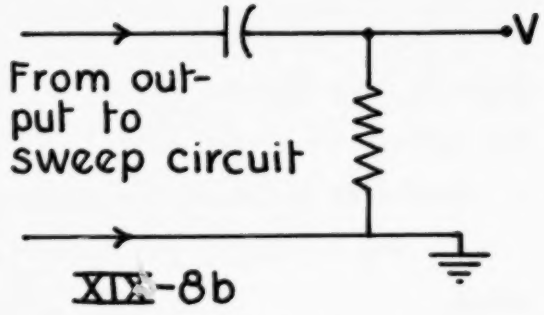


XIX-8a

An interesting way of producing pulses has been recently described*. The output of the sweep circuit of one oscilloscope is used to provide a signal for a second scope. The voltage is obtained from the posts (often located on the back of the

* Jensen, H. C. American Journal of Physics, v. 27, no. 4. April. p. 281

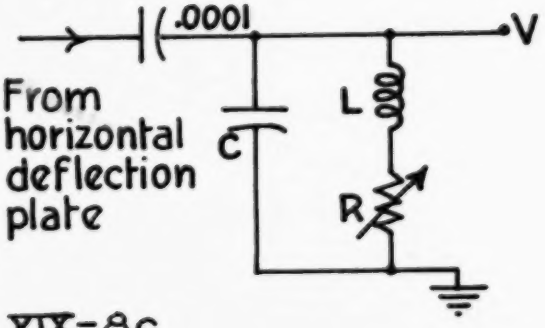
instrument) which are provided for direct access to the horizontal deflecting plates. Connection of the second scope directly to this point shows the expected sawtooth waveform. If a capacitor and resistor are connected as shown in diagram XIX-8b, the output is a sharp pulse. With the sweep frequency at 60 c/sec. the resistor can be about 0.1 megohm and the capacitor 0.001 mfd.



XIX-8b

In experimenting with a triode amplifier it is important to compare the wave-form of the voltage across the plate resistor with that applied to the grid. Changing the grid bias will show distortion due either to cut-off or grid current and overdriving the grid may show both.

An oscilloscope can be used in a particularly interesting study of damped oscillations. A parallel, resonant L-C-R circuit is used. The inductor is a filter choke. The capacitor is a low-loss unit with a capacitance in the range 0.01 to 0.1 mfd. The variable resistor may have a resistance of 10,000 to 20,000 ohms. One side of the circuit is grounded; the other connected to the vertical input terminal of the oscilloscope. The circuit is energized



XIX-8c

by pulses from the oscilloscope's own sweep which are fed through a small capacitor (0.0001 mfd). This capacitor is connected to the binding post intended to be used for direct connection to the horizontal deflection plates of the cathode ray tube. The pulse is thus always applied at the start of the sweep so that the pattern is synchronized. The frequency of the oscillation is changed by changing the capacitance and the damping in the circuit can be varied by means of the resistor. See diagram XIX-8c.

(9) Reproduction of Experimental Curves. The advanced student may wish to explore the possibilities of using an oscilloscope to trace experimental curves which are usually produced by drawing a conventional graph of data. Two of the most instructive are that of the hysteresis curve and the characteristic curves of a triode. The procedures for these will be found described in a number of sources. For example, Brown's Electronics* gives accounts of both experiments.

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* Brown, T. B. Electronics. Wiley. 1956

XX. VELOCITY OF TRANSVERSE WAVES

The velocity of a transverse wave in a stretched cord or spring is shown in many college physics texts to be:

$$v = \sqrt{F/\mu}$$

where v is the velocity, F the tension and μ the mass per unit length or linear density of the transmitting medium. There are many ways of working in the elementary laboratory with this relationship.

It is interesting to make simple direct measurements of all three quantities and compare the calculated and measured values of the velocity. A pulse may be transmitted by a long stretched spring or by a piece of rubber tubing. In the latter case the wave velocity can be reduced by weighting the tubing by filling it with sand. The transmitting medium is clamped at one end, pulled out horizontally, and held at the other end by a cord which passes over a pulley and has weights hanging from it to supply the tension. The disturbance is created by striking it sharply near one end. The pulse then travels to the opposite end, is reflected and returns, usually making several trips back and forth before being lost. A stopwatch is used to time as many transits as can be observed. From the number of trips, the length of the spring or tube and the time, the velocity is calculated. Comparison can then be made with the velocity obtained by applying the formula to the tension and the linear density.

It is also possible to find the velocity of a transverse wave in a cord by creating standing waves, measuring the frequency,

and applying the wave equation $V = f \lambda$. The distance between adjacent nodes is half the wavelength. Thus if there are n antinodes, the length of the string must be $\frac{n\lambda}{2}$, from which the wavelength is easily determined.

Standing waves may be generated in the same physical arrangement described above by holding the stretched spring or tube lightly near one end and quickly moving it up and down. With a little practice the resonant frequencies can be found. If the wave velocity is not too great, and the length is great enough (3 or 4 meters or more) the frequency will be low enough to be measured by timing a counted number of vibrations.

Another interesting way to produce standing waves is to use alternating current to supply the power for the vibration at the frequency of the a.c. An iron wire stretched across the table top has a small a.c.-energized electromagnet near it, and is attracted 120 times a second if the line frequency is 60 c/sec. The same physical setup can also maintain vibrations at 60 vps under different conditions of tension and position of magnet. Again the wave velocity computed from the wave equation is compared with that predicted from the tension and linear density of the wire.

If a brass wire is used, it can be supplied with a.c. from a small transformer, and will vibrate when straddled by a strong permanent magnet. In both foregoing methods the tension is the critical variable and it should be carefully adjusted to give the largest amplitude of vibration.

The same experiment can also be done by driving an ordinary thread or string by an a.c. vibrator that is available commercially.

Since the tension is proportional to the square of the velocity, it is also proportional to the square of the wavelength and a graph of F vs. λ^2 will be linear.

It is also valuable to use this setup to measure the a.c. frequency. Since:

$$f = \frac{v}{\lambda} \qquad \text{and} \qquad v = \sqrt{F/\mu}$$

then: $$f = \frac{1}{\lambda}\sqrt{\frac{F}{\mu}}$$

If F is plotted vertically against λ^2, the slope of the resulting straight line is μf^2, from which the frequency is determined.

Another possibility is to energize the string by vigorous bowing, changing the tension until the frequency matches that of a tuning fork as evidenced by lack of beats. The frequency of the string is then calculated and compared with that of the fork.

XXI. THE DIFFRACTION GRATING AND SPECTRA

The replica grating has been a valued teaching tool for many years. Usable gratings of close spacing and almost any desire size are now available in a very inexpensive form. When a light source is viewed through a grating a spectrum is formed on either side of the source. The angular displacement of the light from the central image depends on its wavelength. The relationship is:

$$\sin \theta = \frac{\lambda}{s}$$

where θ is the angle between the diffracted image and the central image, λ is the wavelength and s the grating spacing.

If the distance from source to grating is L and the perpendicular distance through which the image is apparently displaced from the central image is x, then:

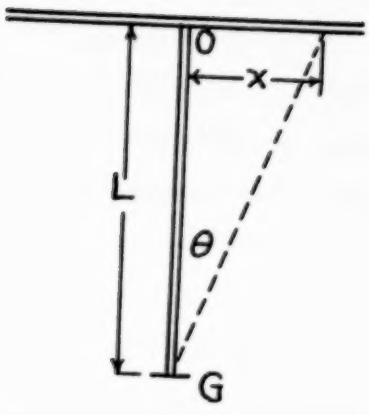
$$\sin \theta = \frac{x}{\sqrt{L^2 + x^2}}$$

Therefore:

$$\lambda = \frac{sx}{\sqrt{L^2 + x^2}}$$

Two 2-meter sticks are mounted at right angles on the table top to form a "T". It is possible to use 1-meter sticks, with loss of accuracy. Refer to diagram XXI. The light source is placed at their intersection (Q) and a grating is mounted on the meter stick which forms the base of the "T" at the point labeled G. The observer then looks through the grating in the direction of the source and sees the spectra on either side of Q against the meter stick. Ingenuity will suggest

various ways of marking the positions of lines or other points of interest in the spectrum. Since for the brighter sources the room need not be completely dark, readings can in some cases be taken directly. In one nice arrangement small flashlight lamps are placed at positions on either side of O. They are then moved until their filaments coincide with the images of the line being measured. The value of x is then half their separation.



XXI

The grating can be held by an optical bench screen mounting or by a lump of "Tacki-wax".

The best source for viewing a continuous spectrum is a straight filament lamp. The yellow light of sodium can be studied by using a sodium flame with a narrow slit in front of it. A fine mercury spectrum against a continuous background is given by a fluorescent lamp. An easy way to make a narrow source of such a light is to use one with a reflector and turn the reflector until only a very thin section of the edge of the tube is visible. Gas discharge tubes of all sorts are available from science supply houses.

A great deal can be accomplished with this simple setup. The first step might be a study of the continuous spectrum. The wavelengths of its visible limits can be measured. The order and wavelengths of the recognizable colors can be studied.

If a rheostat is connected in series with the lamp, the student can observe the change in distribution of the wavelengths of radiated light as the filament temperature is varied. The transmission of light by filters of cellophane, glass or colored solutions offers another field of investigation.

In addition to the obvious measurement of the wavelengths of spectral lines, the procedure can be reversed for one line. By using the known wavelength of this one line as a standard, the grating spacing can be measured.

Materials other than sodium can be placed in the flame to produce their typical spectra.

The second order spectra are visible, but will mostly fall beyond the meter stick scale so that this must be extended for making measurements.

XXII. THE THICK LENS

Making the transition from the simplified situation involving a thin lens to the thick lens, for which refraction at the surfaces must be considered separately, presents a considerable hurdle to the high school student. In the experiment to be described, a thick plano-convex lens is studied, and the basic principles of refraction are applied to its analysis. The index of refraction is computed from the apparent and actual thickness of the lens. The radius of curvature of the spherical surface is obtained from measurements of the thickness and the diameter. Then these quantities are used to predict an image position for a given object position. This can then be compared with the actual result obtained when the lens is used to produce an image.

The fundamental equation for refraction at a surface separating two media is:

$$\frac{n}{s} + \frac{n_1}{s_1} = \frac{n_1 - n}{R}$$

in which the light rays are assumed to be going from left to right, n and n_1 are the refractive indices to the left and right of the surface respectively, s and s_1 are the object and image distances from the surface, and R is the radius of curvature of the surface. The usual sign conventions must be observed; for example, when a ray (coming from the left) encounters a refracting surface, R is positive if the center of curvature lies to the right of the surface, and negative if it lies to the left.

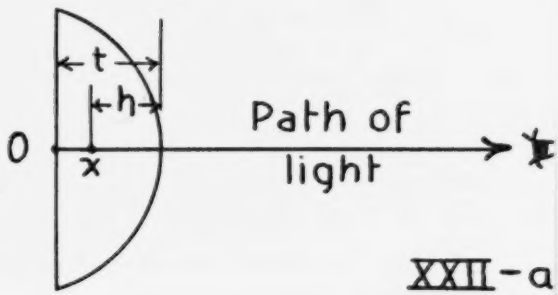
If we look through the center of the curved surface of a large plano-convex lens at a point O on the flat surface, refractio will cause it to appear to be at X, so that the lens thickness is apparently h rather than t. This is illustrated in diagram XXII-a. Applying the refraction equation, we have:

$$\frac{n}{t} + \frac{1}{-h} = \frac{1 - n}{-R}$$

Solving for n, we obtain:

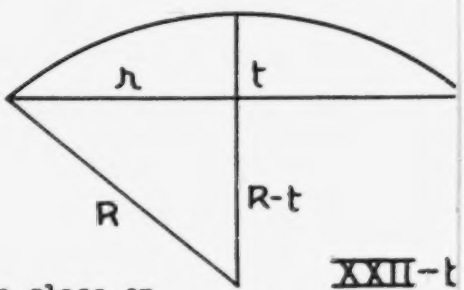
$$n = \frac{t(R - h)}{h(R - t)}$$

All of the values on the right hand side of the equation may be measured, so that the index of refraction can be calculated. To measure R a spherometer may be used. If a spherometer is not available, R can be obtained from the diameter and thickness of the lens. In diagram XXII-b, r is the radius of the plane surface the lens and t is the thickness minus the height of the beveled edg of the lens. (If the lens has no beveled edge, t is the lens thick ness.)



XXII-a

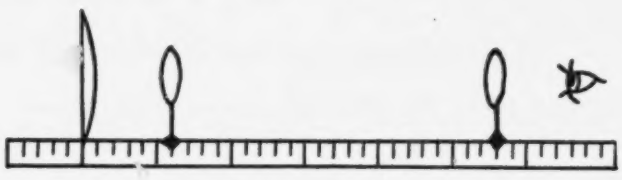
It can be seen that $R^2 = r^2 + (R - t)^2$ from which, $R = \frac{r^2 + t^2}{2t}$ and r as well as t are directly measurable.



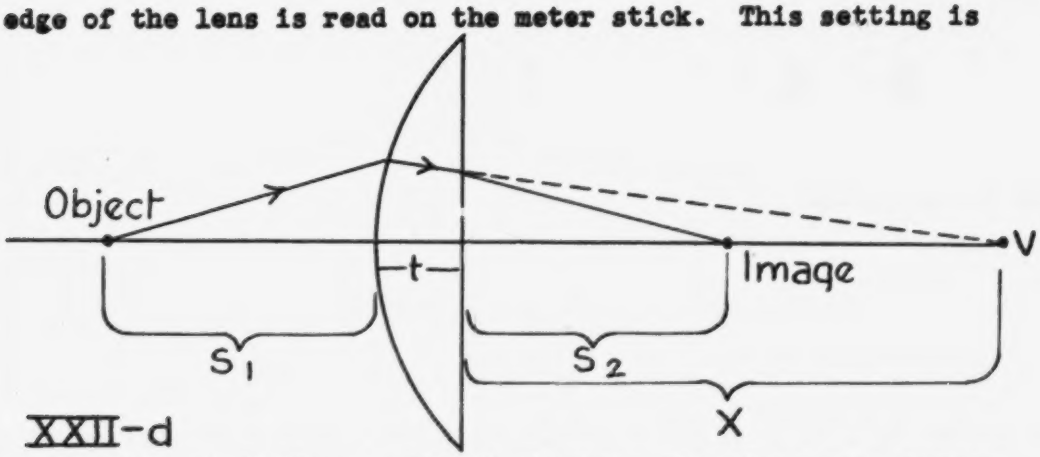
XXII-b

The apparent thickness is measured by using a microscope to focus on the near curved surface and then moving it to focus through the glass on

the plane surface. The distance the microscope must be moved is a measure of apparent thickness. Most schools do not possess a microscope whose motion is along a calibrated scale but a satisfactory substitute can be improvised. Mount two converging lenses on a meter stick to make the type of compound microscope described in the most elementary laboratory manuals. Mount the plano-convex lens separately, its edge touching the meter stick, and its plane surface at right angles to the meter stick, and away from the lenses of the "microscope." A small piece of plastic tape placed at the center of the plane surface serves as an object to sight on. Now the meter stick bearing the microscope is moved longitudinally until the little air bubbles under the tape are clearly in focus (see diagram XXII-c). The position of the edge of the lens is read on the meter stick. This setting is



XXII-c



XXII-d

repeated several times, without changing the microscope lenses, to find an average position. The tape is then moved to the

curved surface and the process repeated. The difference in the two average meter stick indications is h.

Now, with n, R and t determined it is possible to calculate distances when the lens is used to cast an image. By applying the fundamental equation again to the curved and plane surfaces in turn we can obtain an expression involving object and image distances when the lens is actually used. Refer to diagram XXII-d.

By considering paraxial rays and the refraction caused only by the first, or curved surface we have:

$$\frac{1}{s_1} + \frac{n}{X + t} = \frac{n - 1}{R}$$

which can be written as:

$$\frac{1}{s_1} + \frac{1}{\frac{X}{n} + \frac{t}{n}} = \frac{n - 1}{R}$$

For the second, or plane surface where R = ∞:

$$\frac{n}{-X} + \frac{1}{S_2} = 0 \quad \text{or,} \quad \frac{n}{X} = \frac{1}{S_2} \quad \text{or,} \quad \frac{X}{n} = S_2$$

by substitution:

$$\frac{1}{S_1} + \frac{1}{S_2 + \frac{t}{n}} = \frac{n - 1}{R}$$

When S_2 has been calculated the lens may then be used to project an image and the distance S_2 may be checked.

SUPPLEMENTARY PROBLEMS AND EXERCISES

1. Demonstrate that sliding friction depends upon velocity.

2. Demonstrate that the efficiency of a simple machine depends upon the load.

3. Find the moment of inertia of a bicycle wheel.

4. Find empirically the relationship between the period and length of a rod pivoted at the end and used as a physical pendulum.

5. In a conical pendulum, determine how the distance between the plane in which the bob moves and the support depends upon:
   (a) the angular velocity
   (b) the mass of the bob, angular velocity being constant
   (c) the length of the string, angular velocity being constant.

6. (a) Determine how the period of a mass bobbing on two springs connected in series (end to end) is related to its periods on each of the springs separately.
   (b) Determine how the period of a mass bobbing on two springs connected in parallel (side by side) is related to its period on each of the springs separately.

7. Measure the surface tension of several liquids. (An interesting approach is suggested by E. P. Clancy in the American Journal of Physics May 1959 p. 340.)

8. Study trajectories. (A spring gun, easily made or converted from a toy, shoots a marble or steel ball. The angle of elevation is measured by a protractor and the point of impact by having the projectile land on a piece of carbon paper over a "target" sheet.)
   (a) Draw graphs of range versus angle (with the warning that the curve is not a parabola), and range versus the sine of twice the angle.
   (b) Calculate the muzzle velocity.
   (c) Predict the range for some angle not yet tried.
   (d) Estimate the highest point in the trajectory and compare with calculation.

9. Given a simple pendulum, a coiled spring and a set of weights. Find an experimental method of determining the mass to be suspended from the spring so that it has the same frequency as the pendulum. (Use a weight which stretches the spring the same distance as the length of the pendulum. They will then have the same period since:

$$T_{\text{pendulum}} = T_{\text{bobbing weight}}$$

$$2\pi\sqrt{\frac{l}{g}} = 2\pi\sqrt{\frac{m}{k}}$$

$$l = \frac{mg}{k} = \frac{W}{k}$$

10. Demonstrate that the coefficient of restitution depends upon the velocity of collision.

11. Investigate the elastic properties of rubber as compared to the elastic properties of a stressed metal. (In addition to the elongation force graph, the facts of hysteresis and the non-instantaneous response to applied force may be investigated The inverse temperature coefficient when stressed is also interesting.)

12. A U-shaped glass tube contains a liquid. When displaced, the liquid oscillates. Show that this motion is simple harmonic and find the effect on the frequency of:
(a) the density of the liquid
(b) the amount of liquid in the tube
(It should be noted that while the density has no effect, the frequency depends inversely on the square root of the length of the liquid column.)

13. Study accelerated motion by reproducing Galileo's experiment. (The reasoning, method and some direct quotations from Galileo's writings are given in Foundations of Modern Physical Science by Holton and Roller, pp. 28-32.)

14. Determine how the pressure in an inflated balloon varies with the radius. (Measure both during inflation and deflation. Use a manometer. Compare with a soap bubble.)

15. Make a measurement of the mass of a block of metal, without weighing it. (The block can be placed in a car, and accelerated across the table top by means of a falling weight. Note that friction is not neglible and not constant. Another method allows the block which is affixed to the end of a spring or hacksaw blade to vibrate. The equations of simple harmonic motion apply.)

16. Measure the temperature of a dry-ice alcohol mixture. (Since ordinary liquid-in-glass thermometer cannot be used, other temperature-sensitive phenomena should be utilized in designing low temperature measuring devices. Such phenomena include: the expansion of solids, gases and liquids other than mercury, change of electrical resistance with change of temperature and the thermoelectric effect. If the laboratory boasts a low-range thermometer, it should not be used.)

17. Determine how the absorption of infrared radiation depends upon its wavelength. (The radiation from a small heating coil can be detected by a thermopyle. Readings should be taken at various temperatures, with and without an interposed glass plate. The percentage of radiation absorbed by the glass plate is greater at low than at high temperatures.)

3. Determine how the intensity of light transmitted through colored cellophane depends upon the number of thicknesses. (Using a long strip of green cellophane, wrap a photoelectric cell with it. Take a reading of the current after each layer has been added. The light should be focused on the plate of the cell, and stray light excluded. This is an exponential relationship.)

9. Measure the "latent heat of vaporization" of electrons. (A heater-type of diode such as the 6X5 is used. The filament resistance is measured when the plate is negative. Then, with the plate positive, the filament current is readjusted to give the same filament resistance, and therefore, the same temperature. The difference in power can be interpreted as the power needed to produce the electrons of the plate current. The work-function can be evaluated, and the "heat of vaporization" of electrons turns out to be of the order of 8×10^7 cal./g. This has been described by Saunders in the American Journal of Physics Sept. 1953 p. 496.)

). Obtain the characteristic curves of a diode and a triode. (In addition to the usual measurement of μ, r_p and g_m for the triode, operate the triode as an amplifier. Measure its actual amplification with a plate resistor in the circuit, vary the bias, and study the distortion of the signal when the bias and drive amplitude are changed.)

1. Determine what is in the "black box." (A simple electrical circuit is assembled in a box; binding posts to various points are provided. Pupils must make measurements to determine the contents. If a dry cell with a 1000 ohm resistor in series is used to supply current to a variable resistor, a plot of voltage and current readings is linear. The intercept gives the open circuit voltage, and the slope the value of resistance.)

2. Use a slide wire potentiometer to measure an unknown voltage and to calibrate a voltmeter.

3. Make measurements in a simple network to show the application of Kirchoff's Laws.

4. Measure the heat of sublimation of dry ice.

5. Determine how the efficiency of a transformer depends upon the load.

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